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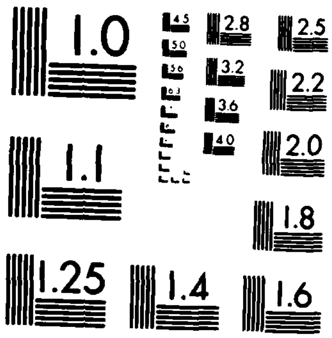

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A COMPUTER PROGRAM FOR DYNAMIC RESPONSE OF LAYERED SATURATED SANDS

Mahantesh S. Hiremath and Ranbir S. Sandhu
Department of Civil Engineering

DEPARTMENT OF THE AIR FORCE
Air Force Office of Scientific Research
Bolling Air Force Base, D.C. 20332

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The "Engineering Approach" to dynamic response analysis of saturated sand deposits is investigated. The logic on which the methodology is based is described and implemented in a computer program. Application of the procedure to obtain dynamic response of a saturated sand layer, including pore pressure, shear stress and acceleration variations under two different ground excitation histories is given. Two alternative numerical procedures are investigated. The results are compared with those reported by Finn. Limitations of the approach are discussed.

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By

Mahantesh S. Hiremath and Ranbir S. Sandhu
Department of Civil Engineering

April 1984

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FOREWORD

The investigation reported herein is part of the research project at The Ohio State University, Columbus, Ohio supported by the Air Force Office of Scientific Research Grant 83-00-55. Lt. Col. John J. Allen was the Program Manager at the commencement of the Project. Lt. Col. Lawrence D. Hokanson was the Program Manager from July 1,1983. The Research project was started in February 1, 1983 and is continuing. The present report documents part of the work done up to January 31, 1984. At The Ohio State University, the Project is being supervised by Dr. Ranbir S. Sandhu, Professor, Department of Civil Engineering. The computer program development and the analyses reported herein were carried out by Mahantesh S. Hiremath, Graduate Research Associate. The Instruction and Research Computer Center at The Ohio State University provided the computational facilities.

ABSTRACT

The 'Engineering Approach' to dynamic response analysis of saturated sand deposits is investigated. The logic on which the methodology is based is described and implemented in a computer program. Application of the procedure to obtain dynamic response of a saturated sand layer, including pore pressure, shear stress and acceleration variations under two different ground excitation histories is given. Two alternative numerical procedures are investigated. The results are compared with those reported by Finn. Limitations of the approach are discussed.

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SECTION I

INTRODUCTION

Since the early forties, the mechanism underyling liquefaction of saturated sands subjected to dynamic loading has attracted the attention of engineers and geologists. Particularly, the events following the earthquakes at Alaska and Niigata in 1964 and the extensive damage caused by liquefaction of soil in both the cases led to extensive geotechnical engineering effort to study of response of saturated sand deposits to earthquake motions. Along with this, the need to consider this problem in design of important structures such as dams, nuclear reactors etc. has played a major role in continued interest in this area.

The effect of earthquake induced shear stresses and shear strains is to cause slip at grain to grain contact, which results in volumetric compaction in dry sands. "In saturated sands however, any volume change of sand implies a corresponding quantity of fluid flowing out. This is necessarily a time depedent process. Hence volumetric compaction takes place gradually by drainage. According to Finn [6], the mechanism of deformation and pore water pressure buildup is as follows: In saturated sands,the volumetric compac-

tion is retarded because the water cannot drain instantaneously to accomodate the volume change. Consequently, the relaxing sand skeleton transfers some of its intergranular or effective stresses to the pore water and the pore water pressure increases. The corresponding reduction in effective stress leads to a structural rebound in the sand skeleton to absorb the difference in volume between the compaction due to the grain slips and the reduction in pore water volume due to increased pore water pressure and drainage. In the extreme case, the pore water pressure developed during the earthquake may increase until all the intergranular or effective stress has been eliminated. In this state, the sand has no significant shearing resistance and deforms like a liquid. Liquefaction is said to have occured".

The early attempts at determining the response to cyclic loading of a horizontally layered sand deposit were based on total stress procedures. The volume changes and the porewater pressures that develop during cyclic loading were assumed to depend upon the shear strains. The dynamic shear strains in turn depended upon the stiffness and damping characteristics of the sand layers. For a horizontal shear wave propagating vertically through a horizontally layered saturated sand deposit, assuming that the sand undergoes simple shear deformations only, the stiffness at any time may be expressed as a function of the shear modulus. In fun-

damental studies of effective stress-strain relations for sands, Seed and Idriss [1] and Hardin and Drnevich [2] showed the shear modulus to be function of the mean effective stress and the shear strain. The initial effective stresses were used in computation of the initial value of the shear modulus. Subsequently, the dependence on shear strains was allowed for. However, increase of the porewater pressure during shaking and consequent decrease in the effective stresses in the layer, which in turn decrease the mean normal effective stresses, was not taken into account in calculating the shear modulus.

An improved method for problems of liquefaction in two dimensional systems using iterative approach was presented by Seed, Lee and Idriss [3]. In study of Sheffield dam, they assigned zero shear modulus to those regions of the dam that liquefied. Proceeding in this manner, it was possible to predict the progressive developement of liquefaction. However, in case of one-dimensional problems, since liquefaction is supposed to occur at the same time at points on the same level, the above method could not be applied. Also, effect of the porewater pressure on the shear modulus prior to liquefaction, was still not accounted for.

Streeter et al [4] illustrated a numerical method of dynamic response, that accounts for the effect of pore pres-

sure. The response of the pore water and the granular skeleton were treated separately as uncoupled problems. Pore pressure effects were incorporated by specifying pseudocyclic and permanent volume changes. However, a method for assigning values to such volume changes was not established.

Liou, Streeter and Richart [5] introduced a different model for the development of pore pressure. A fixed relationship between shear modulus and the constrained rebound modulus was assumed to exist. The adequacy of this model is yet to be established.

It would seem reasonable to expect that a realistic representation of the dynamic response of saturated sand deposit would require allowing for progressive development of pore pressure simultaneously with the dynamic analysis of displacements. A method of effective stress analysis was presented by Finn et al [6]. In this, variation in pore water pressure and strains was allowed by periodic updates. The constitutive laws account for important factors known to affect the response characteristic of saturated sands to dynamic loading, including simultaneous generation and dissipation of pore pressure. This method and its variants are the current state-of-the-art. As part of the present research effort, this 'engineering approach' was implemented in a computer program. Specific application considered was

horizontally layered saturated sand deposits subjected to a horizontal shear wave applied at the base and propagating vertically up. This theory does not allow for continuous and simultaneous changes in pore water pressure and strain. Periodic updates are an improvement over no updates at all but as Christian [24] noted for the case of consolidation of soils, the sequential solution of two differential equations did not give correct solutions and was very sensitive to mesh size. For the case of dynamic response analysis, the need to be careful is even greater. The sequence of occurrences assumed in the 'engineering approach' viz. shear stresses cause volume change, volume change results in pore water pressure changes, pore pressure dissipation follows, pore pressures determine effective stresses, which in turn define shear modulus to be used subsequently represents the physical phenomenon only approximately. The theory has been attractive because of its 'simplicity' and the fact that no alternatives were available. We note that the theory is far from simple insomuch as the procedure depends upon insitu condition of soil deposit and uses empirical relations based on experimentally obtained soil properties. The procedure is site-specific. The numerical solution scheme is not quite reliable. The results of the analysis can thus be only qualitative. The approach cannot determine the post-liquefaction pore pressures correctly. It has been used only for

one-dimensional wave propagation and cannot be extended to two and three-dimensional cases. Use of this theory requires considerable experience and "judgement" in addition to extensive laboratory testing program to get useful results.

Biot's [20] theory of coupled motion and fluid flow has been used by Ghaboussi and Wilson [23] to develop computer program for dynamic response analysis of soils. However, the procedures are applicable only to linear elastic soils, use several other assumptions and have not been verified against either theoretical solutions or experimental data in the laboratory or in the field. An investigation of that approach is the subject of a separate report.

SECTION II covers the theoretical background for the 'engineering approach' including constitutive laws, direct nonlinear analysis, coupled dynamic analysis and pore pressure response. SECTION III describes the example problem. Results of the analysis are given in SECTION IV. SECTION V contains the conclusions of the present study. The computer program description, instruction for usage and Fortran listing along with sample input and output are given in the Appendices.

SECTION II

THEORETICAL FORMULATION

2.1 PHYSICAL INTERPRETATION FOR DYNAMIC RESPONSE

It is generally recognized that the basic cause of liquefaction of saturated cohesionless soils subjected to dynamic loading is the build-up of excess hydrostatic pressure. These stresses could be due to upward propagation of shear waves associated with a seismic event or due to blast or explosion.

In the 'engineering approach', the basic line of reasoning is as follows. As a consequence of dynamic stresses, caused by applied loading, the sand tends to become more compact with transfer of stress to the pore water. As a result, the sand grain structure rebounds to the extent required to keep the volume constant and this interplay of volume reduction and soil structure rebound determines the magnitude of the increase in porewater pressure in the sand deposit. Under reduced effective stress and continued motion slips at the grain contacts are possible resulting in a more stable sand structure under the reduced effective stress

[7]. Actually, the changes in effective stress, skeletal structure and pore water pressure occur simultaneously rather than as a sequence of events listed above. In a more complete theory, these occurrences would be treated as simultaneous.

In the 'engineering approach', to compute the response of saturated sand layers under applied shear excitation, the following factors need to be considered:

1. Initial shear modulus in situ.
2. Variation of shear modulus with shear strain.
3. Generation of pore water pressure due to straining of soil and dissipation thereof due to spatial flow.
4. Changes in effective mean stress.
5. Damping and its influence..
6. Processes leading to increased resistance termed collectively as hardening.

2.2 CONSTITUTIVE RELATIONS

Constitutive relations for dry or saturated sands in simple shear were presented by Finn[8]. These covered the factors cited earlier and subsequent analytical procedures included analysis of dynamic response of saturated sands under field loading conditions along with the dissipation of pore pressure [9,10].

The initial response of sand to dynamic loading depends upon its state in situ, as indicated by its shear modulus G_{m0}. Finn [10] assumed that upto the point of first reversal in loading, the response of the sand follows the hyperbolic stress-strain relationship formulated by Kondner and Zelasko [11] and also adopted by Hardin and Drnevich [2]. This relationship is represented by the following equation:

$$\tau = f(\gamma)$$

or $$\tau = G_{m0}\,\gamma / (1 + G_{m0}\,\gamma / \tau_{m0}) \tag{1}$$

in which τ is the shear stress at the strain amplitude of γ, G_{m0} is the initial maximum tangent modulus and τ_{m0} is the maximum shear that can be applied to the sand in its initial state without failure as shown in Figure (1).

The quantities G_{m0} and τ_{m0} were given in units of pounds per square foot by equations proposed by Hardin [7]. These were modified for horizontal sand layer as [6]

$$G_{m0} = 14760\,[(2.973-e)^2/(1+e)]\,[(1+2k_0)/2]^{1/2}\sqrt{\sigma'_v} \tag{2}$$

$$\tau_{m0} = [[0.5(1+k_0)\sin\phi]^2 - [0.5(1-k_0)]^2]^{1/2}\;\sigma'_v \tag{3}$$

in which e = void ratio and is limited to values less than 2, σ'_v = vertical effective stress in psf, K_0 = coefficient

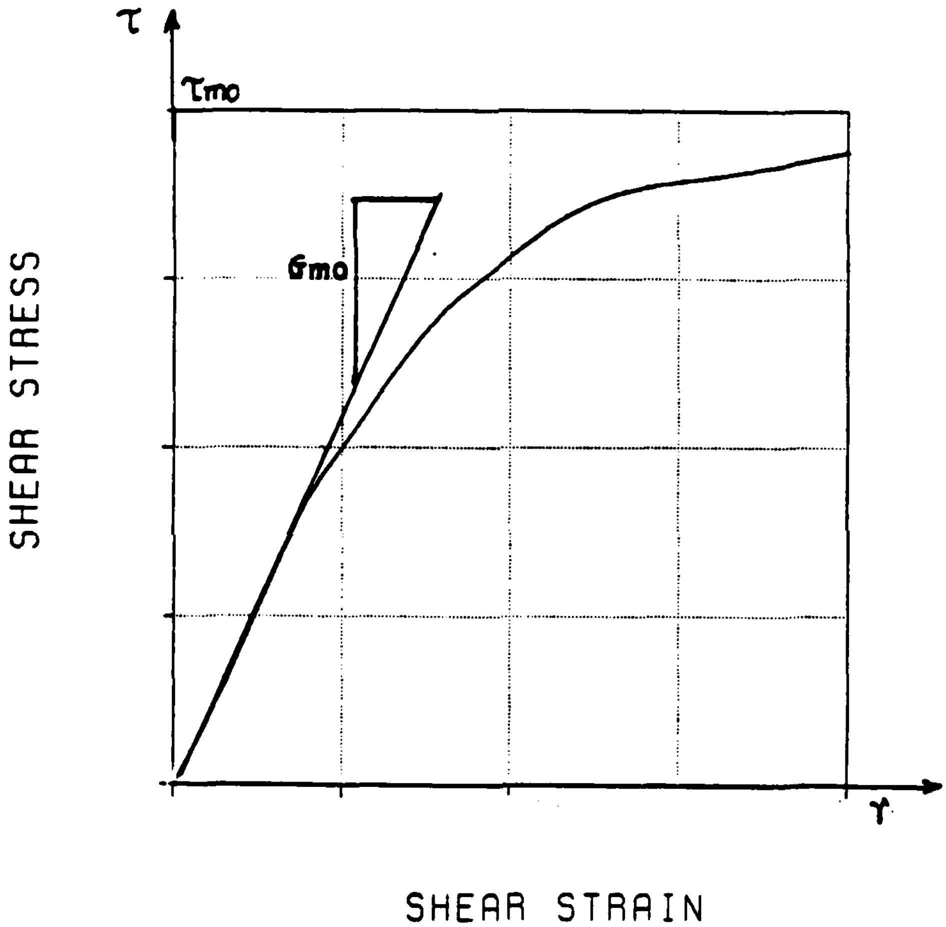

Figure 1: Hyperbolic Stress-strain Curve [6]

of earth pressure at rest and ϕ = effective angle of shear resistance. For unloading or reloading phase, the stress-strain curve is described by Masing's [21] rule i. e.

$$(\tau - \tau_r)/2 = f[(\gamma - \gamma_r)/2] \tag{4}$$

where (τ_r, γ_r) is the point at which loading reversal occurs. Equation (1) through Equation (4) imply that the shear modulus is strain-dependent and damping is hysteretic [8].

2.3 HARDENING AND PORE PRESSURE EFFECTS

During cyclic loading slippage at the grain contacts results in volumetric compaction [7,12,13] and increased value of k_0, the coefficient of effective lateral stress [14]. Both these effects stiffen the sand against further deformation. It is probable that slips at the grain contacts result in a more stable structure under given effective stress [7]. These processes leading to increased resistance are referred to collectively as hardening. Martin [12] suggested a stress-strain relationship in the form

$$\tau_{hv} = \gamma\sqrt{\sigma'_v} / (a + b\gamma) \tag{5}$$

in which τ_{hv} and γ are associated horizontal shear stress and shear strain respectively and σ'_v is the current effect-

ive stress.

The expression for maximum shear modulus G_{mn} amd maximum shear stress τ_{mn} in terms of the initial values G_{m0} and τ_{m0} and volumetric strain ϵ_{vd} are given as

$$G_{mn} = G_{m0} [1 + \epsilon_{vd} / (H_1 + H_2 \epsilon_{vd})] \tag{6}$$

$$\tau_{mn} = \tau_{m0} [1 + \epsilon_{vd} / (H_3 + H_4 \epsilon_{vd})] \tag{7}$$

where ϵ_{vd} is the accumulated volumetric strain and H_1, H_2, H_3 and H_4 are constants.

2.4 GENERATION OF PORE PRESSURE

According to Martin [12], during an undrained shear test, the cyclic shear strain causes an increase in pore water pressure, Δu, expressed as

$$\Delta u = \Delta \epsilon_{vd} /[1/E_r + n_p/K_w] \tag{8}$$

in which E_r = one-dimensional rebound modulus of sand at an effective stress σ'_v and K_w is the bulk modulus of water. For saturated sands $K_w >> E_r$ and therefore Equation (8) becomes

$$\Delta u = E_r \Delta \epsilon_{vd} \tag{9}$$

Finn [8] expected $\Delta\epsilon_{vd}$ to be a function of total accumulated volumetric strain, ϵ_{vd} and amplitude of the shear strain and proposed the relationship

$$\epsilon_{vd} = C_1(\gamma - C_2\,\epsilon_{vd}) + C_3\,\epsilon_{vd}^2/(\gamma + C_4\epsilon_{vd}) \qquad (10)$$

For crystal silica sand with relative density D_r = 45%, Kondner [11] gave the values of the constants as : C_1 = 0.80, C_2 = 0.79, C_3 = 0.45 and C_4 = 0.63, when ϵ_{vd} and $\Delta\epsilon_{vd}$ are expressed as percentages. An expression for the rebound modulus, E_r, at any effective stress level, σ'_v, was given by Martin [12] as

$$E_r = (\sigma'_v)^{1-m} \,/\, m\,K_2\,(\sigma'_{v0})^{n-m} \qquad (11)$$

in which σ'_{v0} = initial value of the effective stress and K_2, m and n are experimental constants. For crystal silica sand at D_r = 45%, the values of K_2, m and n were given by Kondner [11] as 0.0025, 0.43 and 0.62 respectively.

The increment in pore pressure, Δu, during a given loading cycle with maximum shear strain, γ, may now be computed using Equation (9) through Equation (11). For saturated sands, the maximum shear moduli and maximum allowable shear stresses for nth loading cycle are related to initial values by [6]

$$G_{mn} = G_{m0}[1 + \epsilon_{vd}/(H_1 + H_2 \epsilon_{vd})](\sigma'_v/\sigma'_{v0})^{1/2} \tag{12}$$

$$\tau_{mn} = \tau_{m0}[1 + \epsilon_{vd}/(H_3 + H_4 \epsilon_{vd})](\sigma'_v/\sigma'_{v0}) \tag{13}$$

in which σ'_{vo} is the effective vertical stress and σ'_v is the effective vertical stress at the beginning of the n th cycle.

2.5 DISSIPATION OF PORE WATER PRESSURE

If the saturated sand layer can drain during motion, there will be simultaneous generation and dissipation of porewater pressure. Thus, the rate of increase of porewater pressure will be less than for completely undrained sand. The distribution of porewater pressure at time is given by the equation

$$u_{,t} = E_r [(K/\gamma_w)u_{,z}]_{,z} + E_r [\epsilon_{vd}]_{,t} \tag{14}$$

in which a subscripted comma indicates the derivative with respect to the variable(s) following it, u is the pore water pressure, K is the coefficient of permeability and γ_w is the unit weight of water. The term containing ϵ_{vd} represents the internal generation of pore water pressure and is similar to a source term in a heat conduction equation.

The porewater pressure any time is in accordance with Equation (14) and reflects the net effects of contemporaneous generation due to volume change and redistribution due to drainage.

The shear modulus, G, expressed in terms of mean normal effective stress σ'_m was given by Seed [15] as

$$G = 1000\ K_2\ (\sigma'_m)^{1/2} \tag{15}$$

in which K_2 is a parameter that varies with shear strain as shown in Figure (2) for relative density $D_r = 0.45$.

Equation (14) must be solved in conjunction with the equation of motion of the sand layer in order to continually update the values of the pore water pressure during dynamic loading.

2.6 COUPLED DYNAMIC ANALYSIS

Consider a stratum of saturated sand of infinite lateral extent resting on horizontal bedrock. The properties of the stratum may vary only in vertical direction. Let the applied excitation consist of horizontal shear waves applied at the base propagating vertically upwards. The dynamic response in this case, in the 'engineering approach' is be considered equivalent to that of a shear beam.

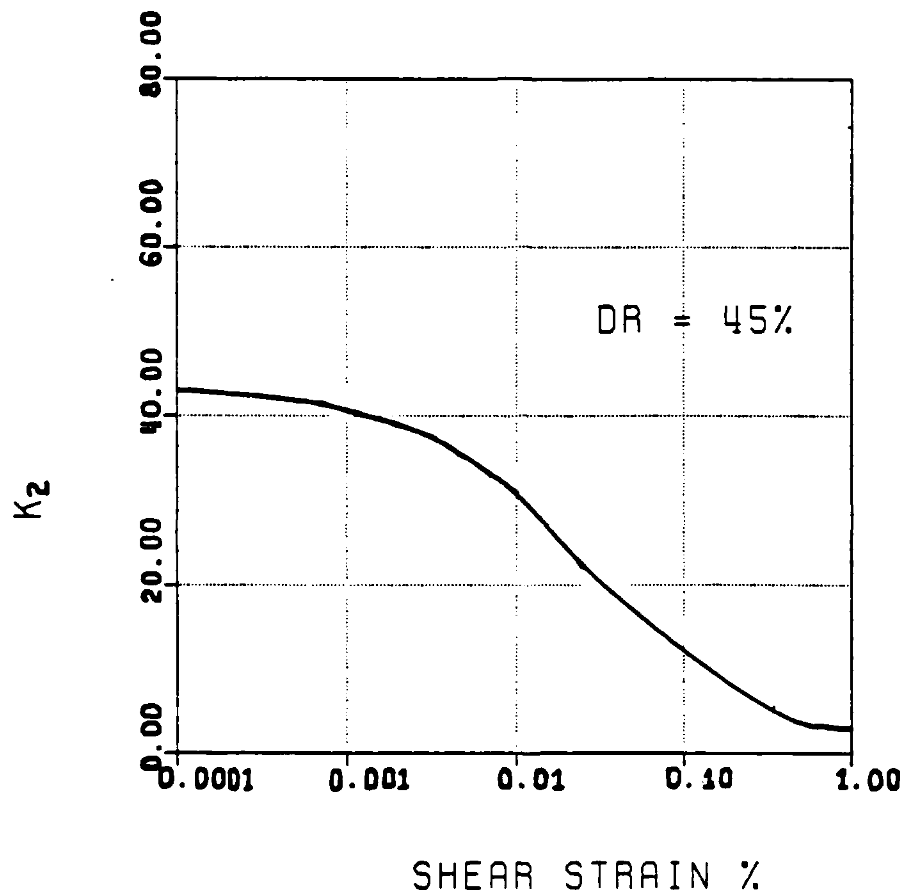

Figure 2: Variation of K_2 vs. Shear Strain in %

2.6.1 Differential Equation of Motion

Since the properties of the soil deposit may vary only along the vertical, the horizontal sand deposit is divided into layers as shown in Figure (3).

The layered system is modelled as a lumped mass system with lumped masses (m_1, m_1, ... m_n). The mass

$$m_1 = \gamma_1 h_1 / (2g) \tag{16}$$

is assigned to the top of the soil layer No.1. Here γ_1 and h_1 are the unit weight and the thickness, respectively, of soil layer No. 1. The other lumped masses associated with inter-layer locations are

$$m_i = [\gamma_{i-1} h_{i-1} + \gamma_i h_i]/(2g) \tag{17}$$

where $i = 1,2,$---------N

The masses are assumed to be connected by non-linear springs having initial properties given by Equation (1) and modified by using Equations (14) and (15). These equations reflect non-linear, strain-dependent, hysteretic behaviour of sand. The spring constants are given by

$$K_i = f(\gamma_i)/ h_i \gamma_i$$

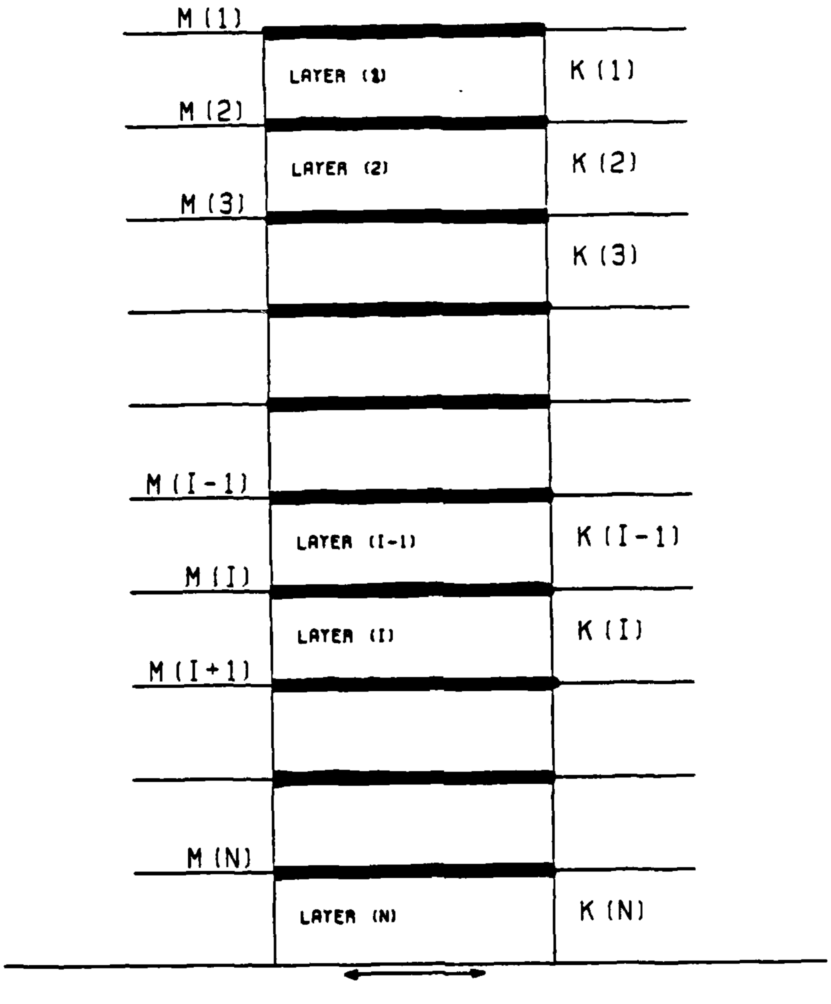

Figure 3: Lumped Mass Representation of the Soil System

or,

$$K_i = G_i / h_i \tag{18}$$

K_i is the spring constant of the spring connecting masses m_i and m_{i+1} and G_i is the shear modulus of the layer i. The equation of motion of the system can be writen as [16],

$$[M]\{\ddot{u}\} + [C]\{\dot{u}\} + [K]\{u\} = \{R(t)\} \tag{19}$$

$[M]$ is the diagonal mass matrix, [C] is the viscous damping matrix, [K] is the tridiagonal symmetric non-linear stiffness matrix, $\{R(t)\}$ is the excitation applied to the system and $\{u\}$, $\{\dot{u}\}$ and $\{\ddot{u}\}$ are the displacements, velocities and accelerations respectively of the masses. Thus,

$$\text{diag } [M] = (m_1, m_2, \text{----------}, m_n) \tag{20}$$

and [K] is a tridiagonal matrix with

$$K_{11} = K_1$$

$$K_{ij} = K_{i-1} + K_i \qquad \text{for } i=j$$

$$K_{ij} = -K_i \qquad \text{for } i=j-1$$

$$K_{ij} = - K_{ji} \qquad \text{for } i=j+1$$

$$K_{ij} = 0. \qquad \text{for all other } i,\ j. \tag{21}$$

The load vector, for the case of acceleration $\{\ddot{u}_g\}$ applied to the base of the system, is given by

$$\{R(t)\} = - \text{col } (m_1, m_2, \text{----------}, m_n) \{\ddot{u}_g\} \tag{22}$$

To set up the damping matrix, which would allow uncoupling of the damping forces in the same way as the uncoupling of the inertia and elastic forces, Caughey [25] proposed use of a finite series in following form

$$C = M\ a_b\ [M^{-1}\ K]^b \tag{23}$$

where b is number of terms in the series and a is proportionality factor. For b = 1, this reduces to Rayleigh damping with C being a linear combination of M and K. In general, damping ratio associated with any mode n is given by [16]

$$\xi_n = 1/(2\ w_n)\ a_b\ w^{2b} \tag{24}$$

A special case of Rayleigh damping is the stiffness proportional damping in which

$$[C] = a_1 \, [K] \tag{25}$$

Here the higher modes of the structure are very heavily damped, since damping ratio is directly proportional to frequency. The fundamental natural frequency of a cohensionless soil strata of depth H, shear modulus G and unit weight of γ is given by [17]

$$w_n = 1.7510 \sqrt{G/\rho} \;/(1.2)\;(H)^{5/6} \tag{26}$$

In the present analysis, the natural frequency of the stratum was calculated taking the values of H, G and of the saturated portion only using Equation (26) and then it was used in Equation (24) to calculate a_1.

2.7 SOLUTION OF THE DYNAMIC EQUATIONS OF MOTION

Following Finn [6], Equation (19) was solved numerically using Newmark's unconditionally stable integration operator [18]. For completeness, the method is described briefly in the following paragraphs.

2.7.1 Newmark's Method

If u, $\dot{u}$ and $\ddot{u}$ denote the displacements, velocities and accelerations respectively, then Newmark's method assumes,

$$\dot{u}(t+\Delta t) = \dot{u}(t) + [(1-\delta)\ddot{u}(t) + \delta\ddot{u}(t+\Delta t)]\,\Delta t \qquad (27)$$

$$u(t+\Delta t) = u(t) + \dot{u}(t)\Delta t + [(0.5-\alpha)\ddot{u}(t) + \alpha\ddot{u}(t+\Delta t)\,\Delta t^2 \qquad (28)$$

where δ and α are parameters that can be determined to obtain integration accuracy and stability. Newmark [18] proposed an unconditionally stable scheme of constant-average-acceleration, in which case $\delta = 0.50$ and $\alpha = 0.25$. The equilibrium Equation (19) at time $(t+\Delta t)$ is used to evaluate $\ddot{u}(t+\Delta t)$ i.e.

$$[M]\,\ddot{u}(t+\Delta t) + [C]\,\dot{u}(t+\Delta t) + [K]\,u(t+\Delta t) = \{R(t+\Delta t)\} \qquad (29)$$

From Equation (28), $\ddot{u}(t+\Delta t)$ is,

$$\ddot{u}(t+\Delta t) = [1/(\alpha\Delta t^2)]\,[u(t+\Delta t) - u(t) - \dot{u}(t)\,\Delta t]$$

$$- (0.5\alpha - 1)\,\ddot{u}(t)$$

Substituting this in Equation (27), an expression for $\dot{u}(t+\Delta t)$ is obtained in terms of $u(t+\Delta t)$ as,

$$\dot{u}(t+\Delta t) = [1 - \delta/\alpha]\,\dot{u}(t) + [(2 - \delta/\alpha)\,\Delta t/2]\,\ddot{u}(t)$$

$$+ [\delta/\alpha\,\Delta t]\,[u(t+\Delta t) - u(t)]$$

These two equations can be used in Equation (29) to get following

$$u(t+\Delta t)\,[K + M\,(1/\alpha\,\Delta t^2) + C\,(\delta/\alpha\Delta t)]$$

$$= R(t+\Delta t) + M\,[(1/\alpha\Delta t^2)u(t) + (1/\alpha\,\Delta t)\dot{u}(t) + (1/2\alpha - 1)\ddot{u}(t)]$$

$$+ C\,[(\delta/\alpha\Delta t)u(t) + (\delta/\alpha - 1)\,\dot{u}(t) + (\Delta t/2)\,(\delta/\alpha - 2)\,\ddot{u}(t)] \quad (30)$$

2.7.2 Algorithm for Newmark's Method

1. Form matrices [M], [C] and [K].

2. Initialize $u(0)$, $\dot{u}(0)$ and $\ddot{u}(0)$.

3. Select time step Δt, parameters δ and α such that stability conditions [22]

$$\delta > 0.5$$
$$\alpha \geq 0.25\,(0.50 + \delta)^2$$

are satisfied.

4. Calculate the coefficients

$a_0 = 1/(\alpha \Delta t)^2 \qquad a_1 = \delta/(\alpha \Delta t)$

$a_2 = 1/(\alpha \Delta t) \qquad a_3 = 0.5\alpha - 1$

$a_4 = \delta/\alpha - 1 \qquad a_5 = 0.5\ (\Delta t)(\delta/\alpha - 2)$

$a_6 = \Delta t\ (1 - \delta) \qquad a_7 = \alpha \Delta t$

5. Form effective $[\hat{K}] = [K] + a_0[M] + a_1\ [C]$ (31)

6. For each time step:

a) Calculate effective load at time (t+ t).

$$\{\hat{R}\ (t+\Delta t)\} = \{R(t+\Delta t)\}$$
$$+ [M]\ [a_0\ u(t) + a_2\ \dot{u}(t) + a_3\ddot{u}(t)]$$
$$+ [C]\ [a_1 u(t) + a_4 \dot{u}(t) + a_5\ \ddot{u}(t)] \tag{32}$$

b) Solve for displacements at time $(t+\Delta t)$.

$$[\hat{K}]\ \{u(t+\Delta t)\} = \{R(t+\Delta t)\} \tag{33}$$

c) Calculate accelerations and velocities at time $(t+\Delta t)$ using

$$\ddot{u}(t+\Delta t) = a_0[u(t+\Delta t) - u(t)] - a_2\ \dot{u}(t)$$
$$- c_3\ \ddot{u}(t) \tag{34}$$

$$\dot{u}(t+\Delta t) = \dot{u}(t) + a_6\, \ddot{u}(t) + a_7\, \ddot{u}(t+\Delta t) \tag{35}$$

2.8 PORE PRESSURE DISTRIBUTION

In order to calculate the pore water pressure, Finn [6] proposed use of equation (14) viz.

$$u_{,t} = E_r\, [(K/\gamma_w)\, u_{,z}]_{,z} + E_r\, [\epsilon_{vd}]_{,t}$$

If the stratum is mechanically and hydraulically homogeneous, then K and γ_w are independent of z. In that case, the above equation reduces to

$$u_{,t} = E_r\, (K/\gamma_w)\, [u_{,zz}] + E_r\, [\dot{\epsilon}_{vd}]_{,t} \tag{36}$$

Setting $D = E_r\, K/\gamma_w$,

$$u_{,t} = D\, [u_{,zz}] + E_r\, [\epsilon_{vd}]_{,t} \tag{37}$$

Two classes of methods, explicit and implicit, are available for solution of Equation (37). In following sections, we describe both these procedures.

2.8.1 Explicit Method

For a general diffusion equation of the type

$$u_{,t} = D\,[u_{,zz}] + Q_{,t} \tag{38}$$

Using forward differences in the time domain and central differences spatially, Equation (38) is discretized to give the explicit relationship

$$u_j^{n+1} = u_j^n$$
$$+ (D\,\Delta t/h^2)[u_{j+1}^n - 2\,u_j^n + u_{j-1}^n]$$
$$+ [\,Q_{j+1}^{n+1} - Q_j^n\,] \tag{39}$$

where the superscripts refer to the time step number and the subscripts indicate the number of the mesh point in the spatial partition. The difference formula is illustrated by a diagram in Figure (4).

It is noted that value of u at time T_{n+1} at point x_j depends on the value of the function at earlier time T_n and not on any value of the current time. For stability, this method requires [19] that the value of the term $[D\Delta t/h^2] < .5$ where h denotes the length of the spatial interval. Noting that for continued saturation by an incompressible fluid the flow equals the volumetric strain, Equation (39) may be writen as

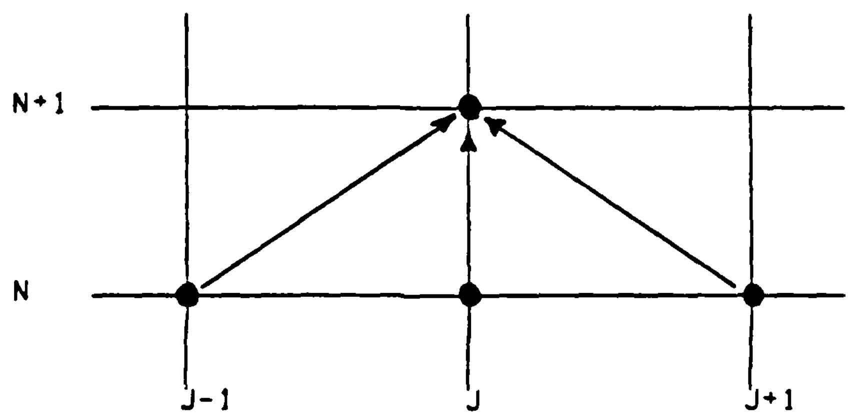

Figure 4: Computational Molecule for Explicit Method

$$[u_j^{n+1} - u_j^n] = [D\,\Delta t/h^2]\,[u_{j+1}^n - 2\,u_j^n + u_{j-1}^n]$$

$$+ [\epsilon_{vdj}^n - \epsilon_{vdj}^n]\,E_r \tag{40}$$

or

$$u_j^{n+1} = u_j^n$$

$$+ [D\,\Delta t/h^2]\,[u_{j+1}^{n+1} \quad - 2\,u_j^n \quad + u_{j-1}^n]$$

$$+ [u_{j+1}^n - 2\,u_j^n + u_{j-1}^n]$$

$$+ [\epsilon_{vdj}^{n+1} - \epsilon_{vdj}^n] \tag{41}$$

Setting $\boldsymbol{\beta} = [D\ \Delta t/h^2]$, Equation (41) has the form

$$u_j^{n+1} = u_j^n + \boldsymbol{\beta}\,[u_{j+1}^n - 2\,u_j^n + u_{j-1}^n]$$

$$+ [E_r]\,[\Delta\epsilon_{vd}] \tag{42}$$

2.8.2 Implicit Method

The implicit method using finite differences called Crank-Nicolson scheme avoids the stability requirement of the explicit method [19]. Thus, Equation (38) can be writen using central difference to approximate both spatial and temporal derivatives as

$$u_j^{n+1} - u_j^n = (D\,\Delta t/2h^2)\,[u_{j+1}^n - 2u_j^n + u_{j-1}^n$$

$$+ u_{j+1}^{n+1} - 2\,u_j^{n+1} + u_{j-1}^{n+1}]$$

$$+ [Q_j^{n+1} - Q_j^n] \qquad (43)$$

Letting $\beta = (D\,\Delta t/h^2)$,

$$-\beta u_{j+1}^{n+1} + 2(1+\beta)\,u_j^{n+1} - \beta u_{j-1}^{n+1} =$$

$$\beta u_{j+1}^n + 2(1-\beta)\,u_j^n + \beta u_{j-1}^n + \Delta Q$$

$$(44)$$

where ΔQ denotes $(Q_j^{n+1} - Q_j^n)$. Thus, for finding the solution at time (n+1) requires the solution of a set of linear algebraic equations. Since the system is tridiagonal, the cost per time step of this method is much greater. But, this method is an order of magnitude more accurate and unconditionally stable. It permits use of a larger time step resulting in significant overall economy, for comparable accuracy, over the explicit method. The computational molecule of the method is shown in Figure (5).

It is noted that expression for $\Delta\epsilon_{vd}$ over the time step

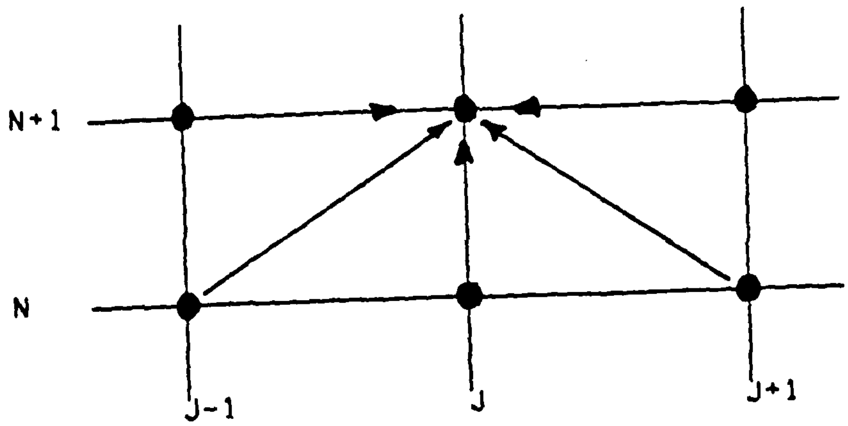

Figure 5: Computational Molecule for Implicit Method

Δt is known from Equation (10). Equation (42) or Equation (44) yields the increase in the porewater pressure for the time interval Δt. The net effective vertical stress is modified using the value obtained from Equation (42) for increase of porewater pressure. Equation (15) can then be used to get the new value of shear modulus.

2.9 ALGORITHM FOR EFFECTIVE STRESS ANALYSIS

Using the procedure outlined for solving dynamic equation of motion in conjunction with the diffusion equation, the algorithm for the computer program implementing the 'engineering approach' is as follows:

1. Set up the mass matrix using Equation(17).
2. Set up initial stiffness matrix using Equation(1) through Equation(3) and Equation(18) through Equation (21).
3. Set up damping matrix using Equation(25).
4. Set up the load vector using Equation(22).
5. For suitable time interval use Newmark's method to find displacements of the lumped masses. Also calculate shear strains using these displacements for each layer of the stratum.
6. Repeat step 5 till stage for changing shear modulus is reached. Find the maximum shear strain upto this stage.

7. Use Equation (10) find the change in the volumetric strain for the largest value of shear strain and add it to the initial volumetric strain to get the cumulative volumetric strain.
8. Using the value of change in volumetric strain obtain the distribution of porewater pressure at that stage.
9. Obtain the new values of net effective porewater pressure and from Figure (2) and Equation (15) find the new values of shear modulus for each layer.
10. Update stiffness and hence damping matrix for new values of shear modulus.
11. Repeat steps 1 through 10.

The computer program based on the above scheme is described in the Appendices.

SECTION III

EXAMPLES OF COMPUTER PROGRAM USAGE

3.1 ILLUSTRATIVE PROBLEM

3.1.1 Introduction

The computer program 'SAND' described in the appendices was used to solve a problem previously analysed by Finn [6]. A saturated layered sand deposit is shown in Figure (6). The 50 ft deep sand stratum had relative density of 45% with water table 5 ft below the surface. Following [6], the basic properties of sand used were:

1. Angle of shear resistance ------------ 40^o
2. Unit weight of saturated sand --------122.0 pcf
3. Buoyant weight of sand --------------- 60.0 pcf
4. Specific Gravity of sand ------------- 2.65

The following relations were used to calculate void ratio and dry density of sand.

$$e = (G\gamma_w - \gamma_{sat})/(\gamma_{sat} - \gamma_w)$$

$$\gamma_{dry} = (\gamma_{sat} - \gamma_w)\, G\, /\, (G-1)$$

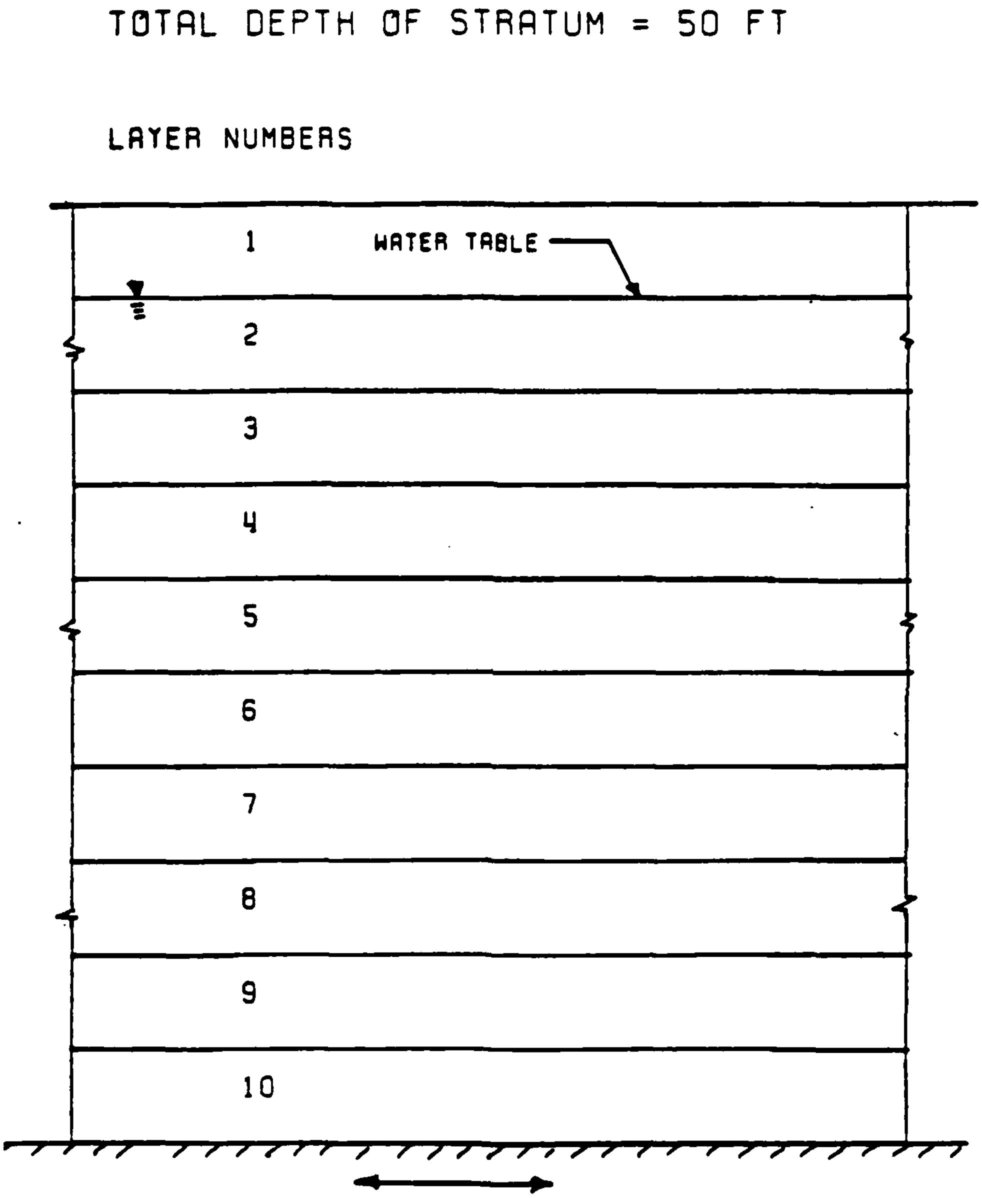

Figure 6: Layered Sand System for Analysis

where e = void ratio, G = specific gravity, γ_{sat} = unit weight of saturated sand, γ_{dry} = unit weight of dry sand and γ_w = unit weight of water. In addition, following numerical values used by Finn [6] were taken for analysis purpose.

1. Total time of excitation ---------------- 10 seconds
2. Time interval (changing shear modulus) 0.5 seconds
3. Time interval (step-by-step integration) 0.01 seconds
4. Time interval (diffusion equation) ------ 0.5 seconds
5. Number of sand layers ------------------- 10
6. Number of spatial divisions ------------- 18
7. Stiffness proportional damping was assumed.
8. Damping ratio (defined as ratio of damping to critical damping) : Several different values were used. These included 0.02, 0.10 and 0.15.

3.1.2 Example 1

A sinusoidal acceleration with a frequency of 2 cycles per second and with a maximum acceleration of 0.805 ft/s was applied at the base of the soil system (Figure 7). For this case, in addition to the three different damping ratios listed in item 8 of 3.1.1, a damping coefficient indepedent of frequency was used. This corresponds to a value of 0.02 for the constant a_1 in Equation (25).

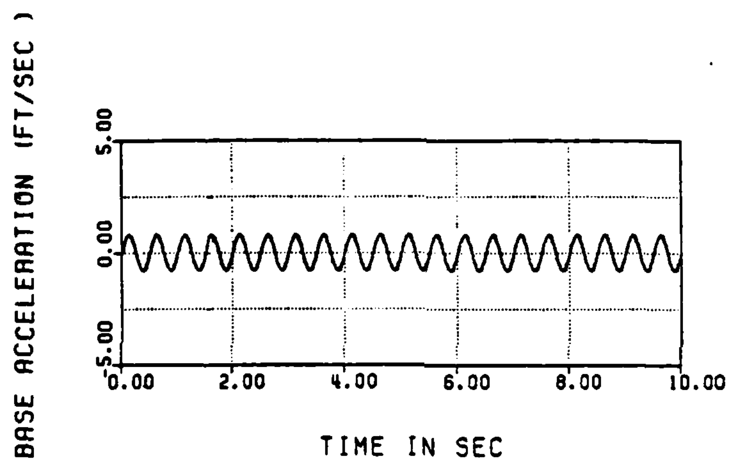

Figure 7: Harmonic Base Input

3.1.3 Example 2

The sand stratum described above was subjected to the earthquake excitation of the first 10 s of the North-South component of the El Centro earthquake (1940) scaled to 0.1g maximum acceleration (Figure 8).

3.2 DISCRETIZED MODEL

The dynamic response was obtained for the sand system, using lumped mass representation shown in Figure (9). The ten sand layers were lumped into ten masses using the approach illustrated in Figure (3). The masses were numbered , beginning with 1 at the top, to 10 at the intersection of 9 th and 10 th layer. The ground water was assumed to be at the top of the second layer i. e. the soil system was saturated from 5 ft. below the surface. For spatial division in diffusion equation, the saturated part of the system was divided into 18 equal layers each of 2.5 ft. The nodes for the finite difference scheme were numbered beginning with 1 at the base to 19 at the water table level.

3.3 METHOD OF SOLUTION

Algorithm established in Section II was used for analysing the dynamic response of the soil system. Newmark's

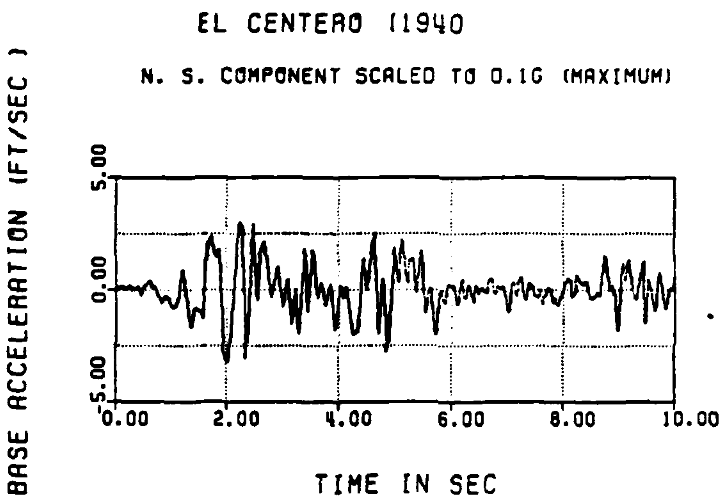

Figure 8: Earthquake Base Input

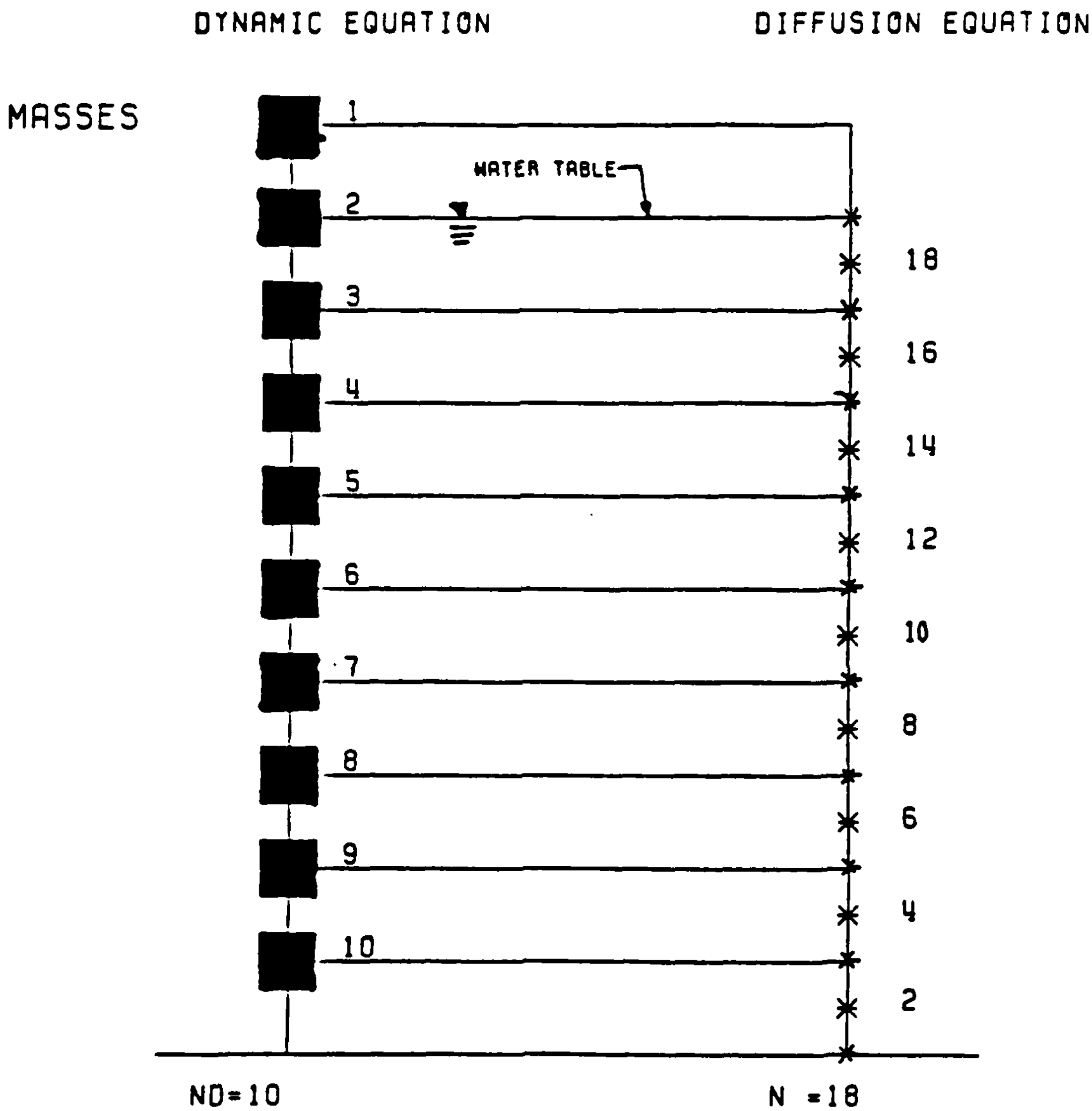

Figure 9: Discrete Model for Sand System

method with $\delta = 0.5$ and $\alpha = 0.25$ was used in solution of dynamic equation while explicit and implicit methods were applied for solving the diffusion equation. After liquefaction takes place at any layer in the system no shear stresses can be transmitted across that layer. However, in the computer program, to control the computational stability, residual stiffness was retained by specifying that the vertical effective stress shall not be less than 10^{-5} of the initial effective stress σ'_{v0} [6].

SECTION IV

RESULTS OF ANALYSIS

4.1 EXAMPLE-1

Both the explicit and the implicit method were used for analysis of dynamic response of the system in Example-1. The results were obtained for different values of damping ratio viz. 0.02, 0.10 and 0.15 for the explicit method and 0.02 and 0.10 for the implicit method. Furthur, the problem was also studied using the damping coefficient to be equal to 0.02, thus making it frequency-independent.

4.1.1 Surface Acceleration

The acceleration response for the entire excitation period was obtained using the explicit method and the implicit method for the case $\xi = 0.02$. Graphical representation of this for explicit method is shown in Figure (10) and that for the implicit method in Figure (11). The values of the maximum surface acceleration for the various cases are shown in Table (1).

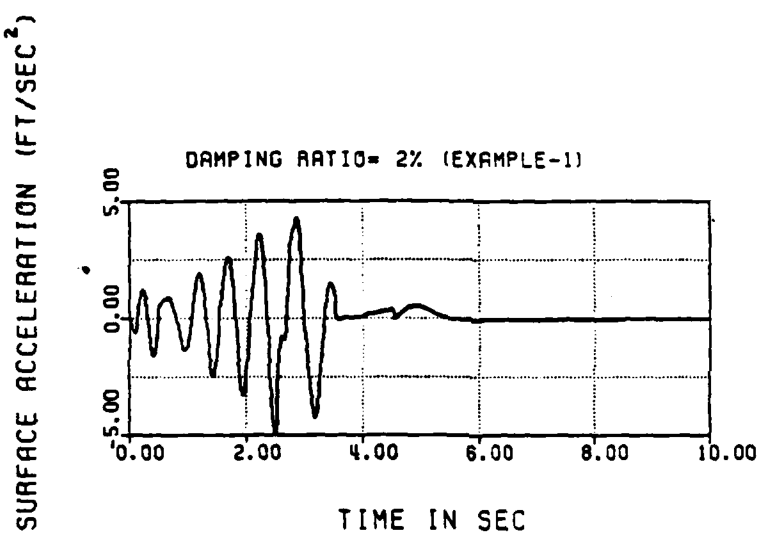

Figure 10: Example-1 Surface Acceleration (ξ = 0.02)

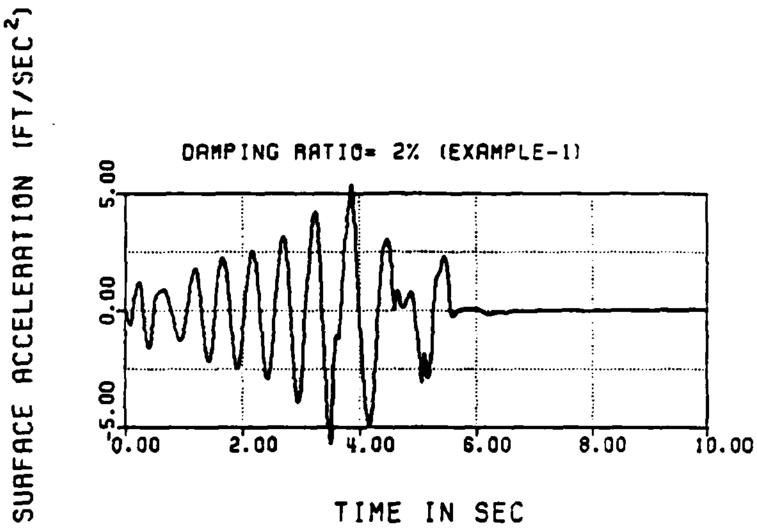

Figure 11: Example-1 Surface Acceleration (ξ= 0.02)

TABLE 1

Example-1 Maximum Acceleration and Shear Stress

Damping ratio or coefficient	Maximum Surface Acceleration (ft/second^2)		Maximum Shear Stress (psf)	
	Explicit Method	Implicit Method	Explicit Method	Implicit Method
$\xi = 0.02$	5.0	5.20	480.0	501.0
$\xi = 0.10$	3.63	4.20	332.8	390.5
$a_1 = 0.02$	3.59	3.75	288.5	335.8
$\xi = 0.15$	3.19	...	257.3	...

4.1.2 Shear Stress Variation

The shear stress variation for the layer that liquefied first is shown in Figures (12) and (13) for the explicit and the implicit method respectively. This is for the case of $\xi = 0.02$. The maximum values of the shear stress for the liquefied layer for different values of damping ratios are shown in Table (1).

4.1.3 Pore Pressure Distribution

The effect of the pore pressure build-up on the effective stress of the system for different values of damping ratio and for constant damping coefficient is shown in Figures (14) through (20). Table (2) shows the time and location of liquefaction for various cases studied. Results for pressure distribution are listed in Tables (3) through (9).

4.2 EXAMPLE-2

A similar analysis was carried out for Example-2 but here only one value of damping ratio equal to 0.02 was used. The variation for the surface acceleration for the explicit method and the implicit method are shown in Figure (21) and (22).

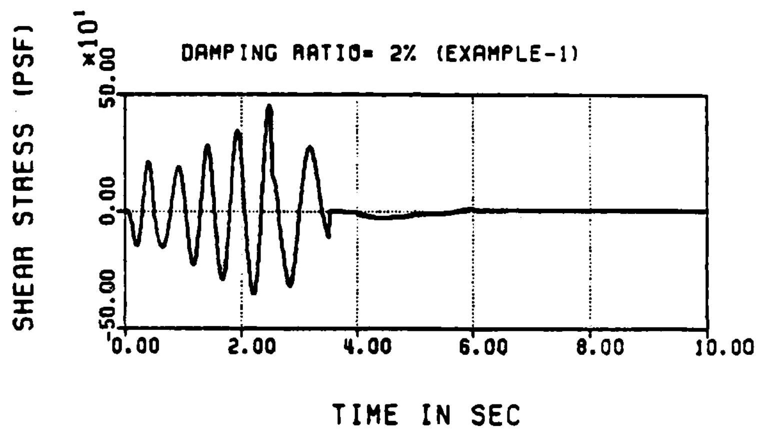

Figure 12: Example-1 Shear Stress (ξ = 0.02)

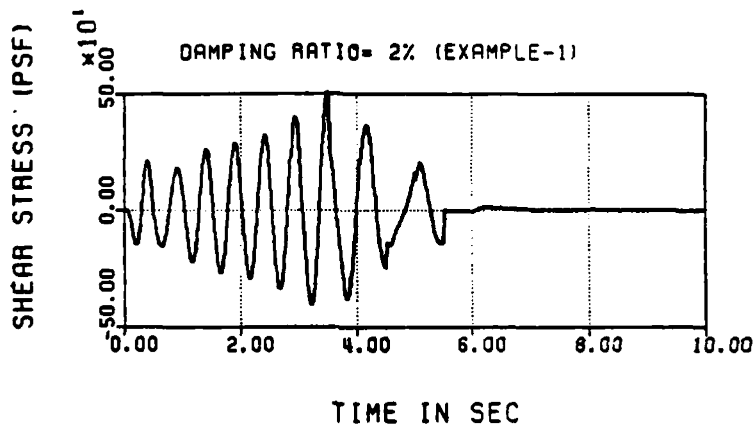

Figure 13: Example-1 Shear Stress (ξ = 0.02)

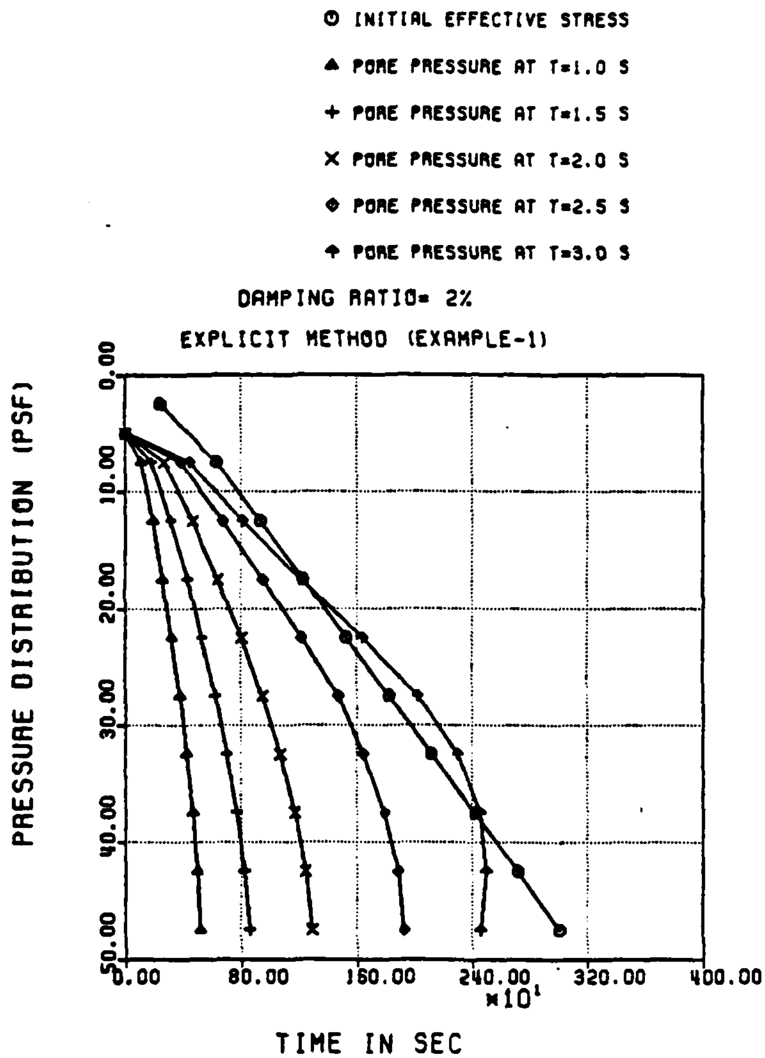

Figure 14: Example-1 Pressure Distribution (ξ = 0.02)

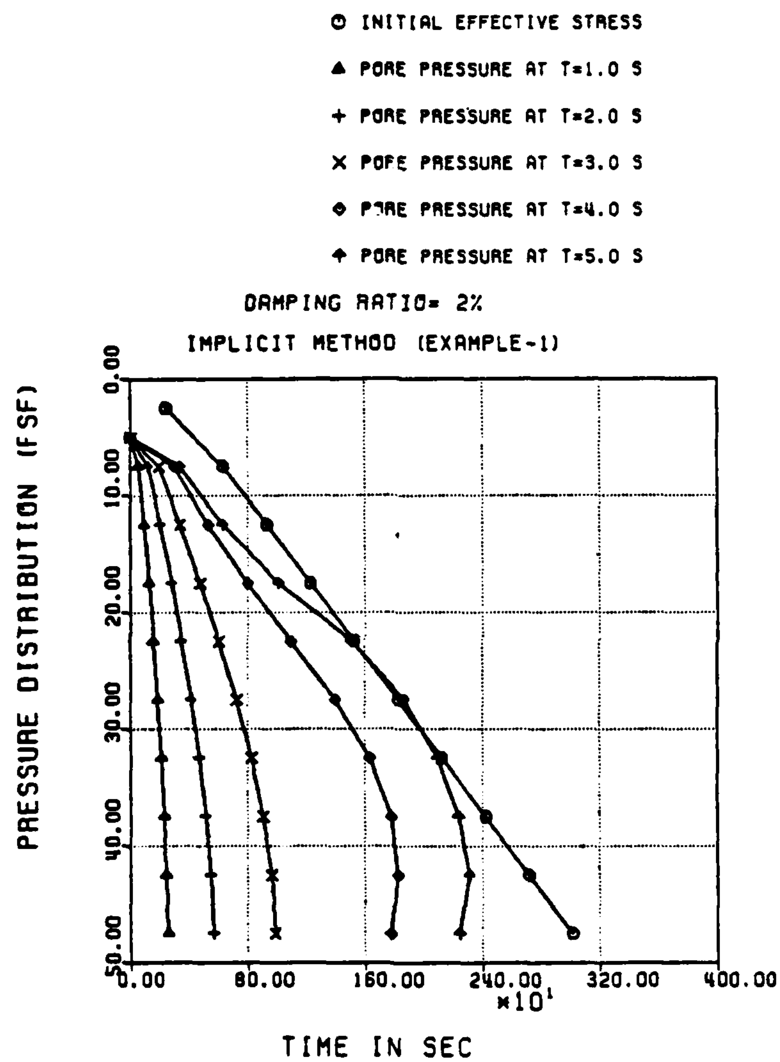

Figure 15: Example-2 Pressure Distribution (ξ = 0.02)

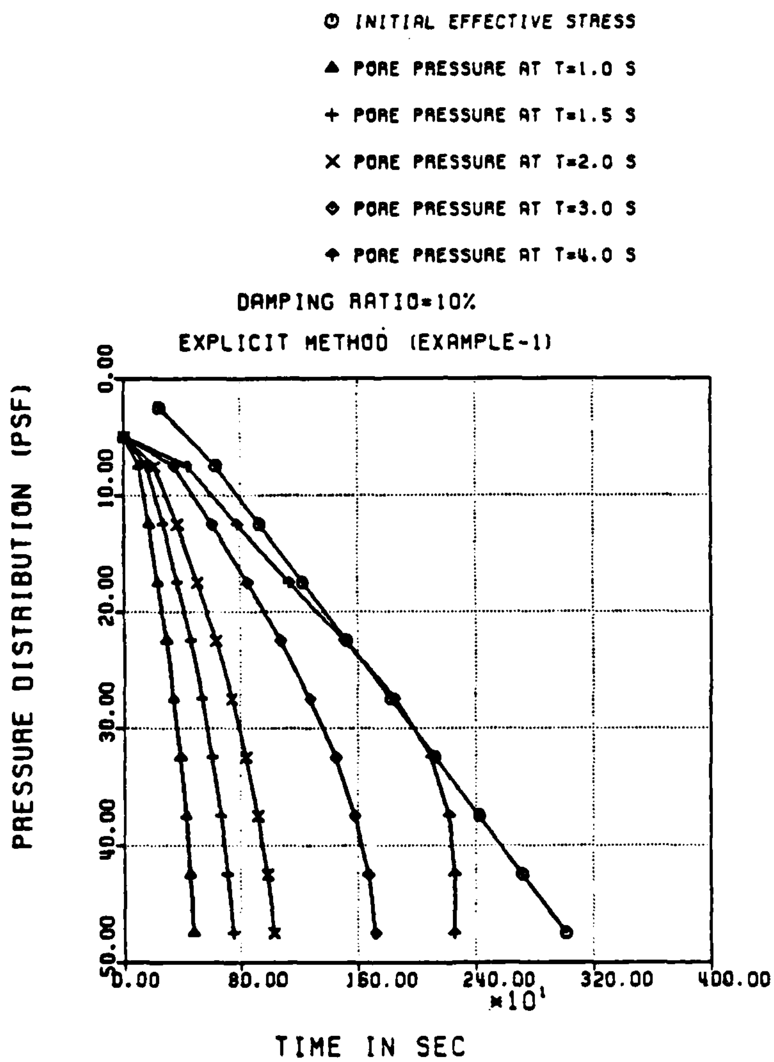

Figure 16: Example-1 Pressure Distribution (ξ = 0.10)

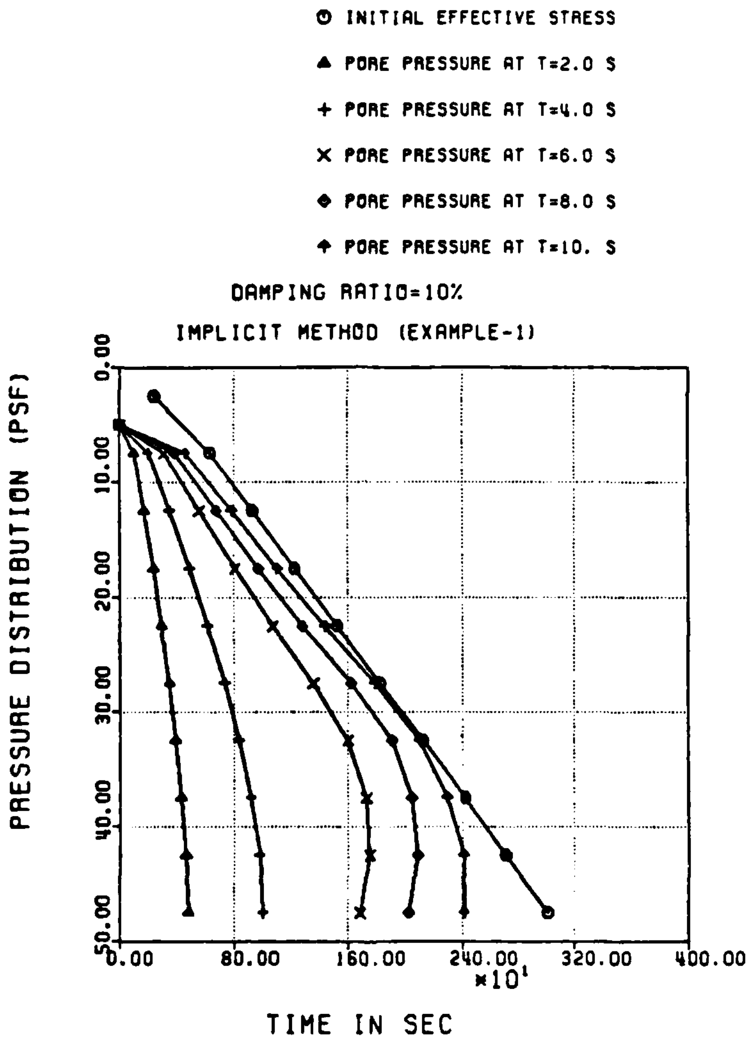

Figure 17: Example-1 Pressure distribution (ξ = 0.10)

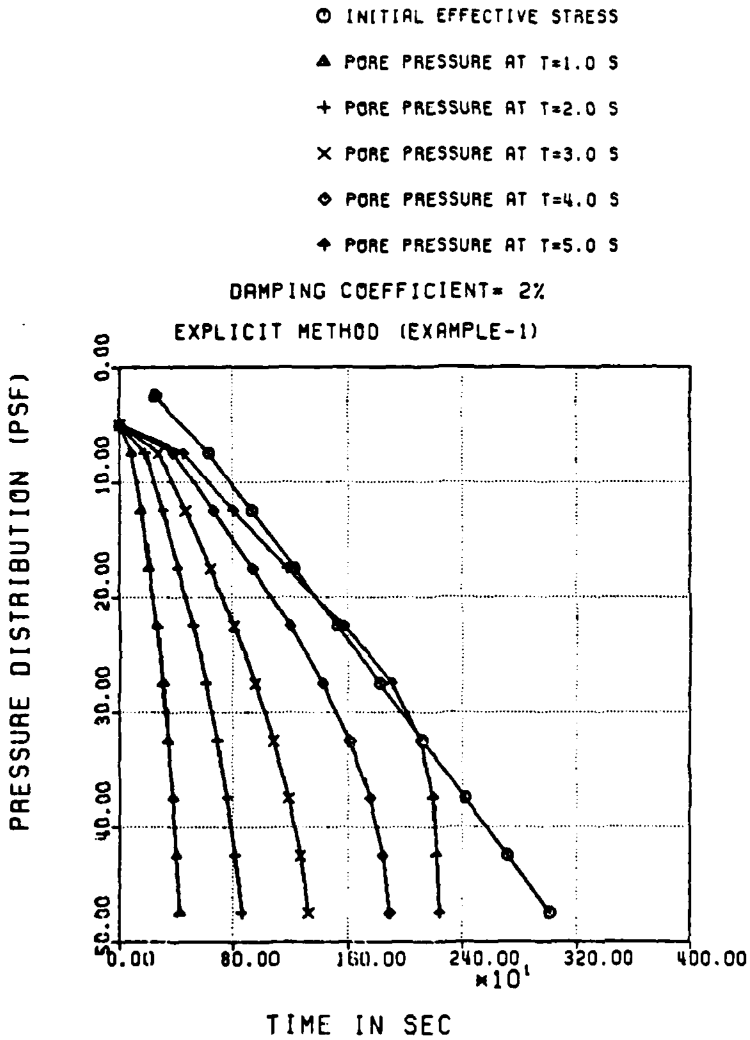

Figure 18: Example-1 Pressure Distribution (a_1 = 0.02)

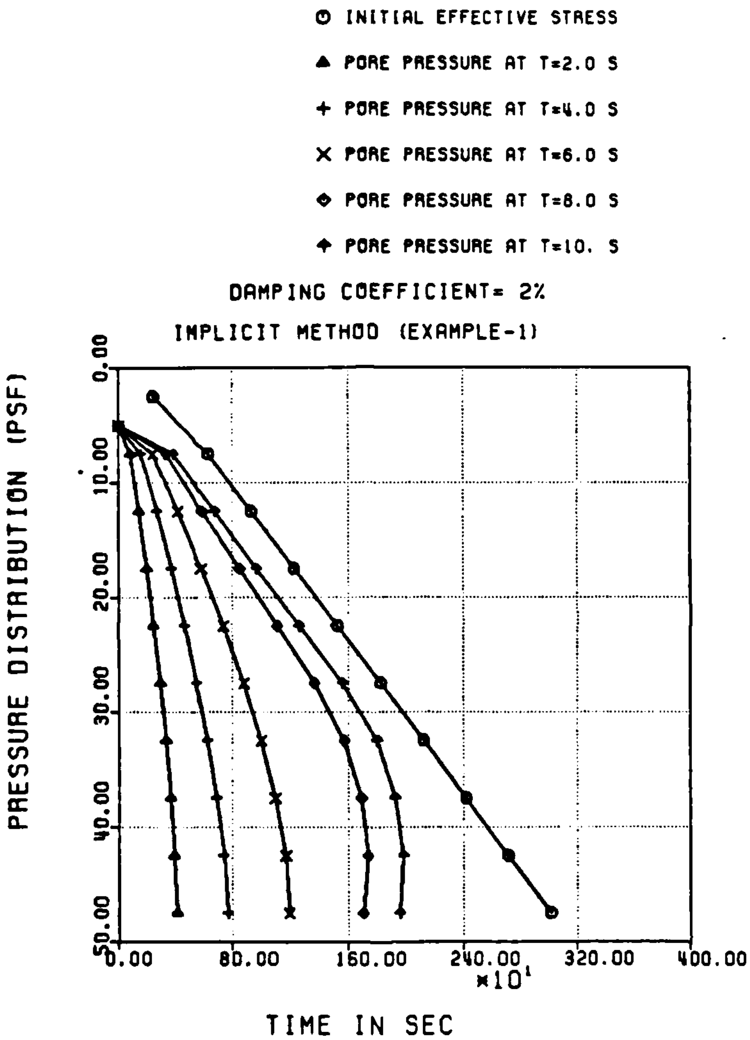

Figure 19: Example-1 Pressure Distribution (a_1 = 0.02)

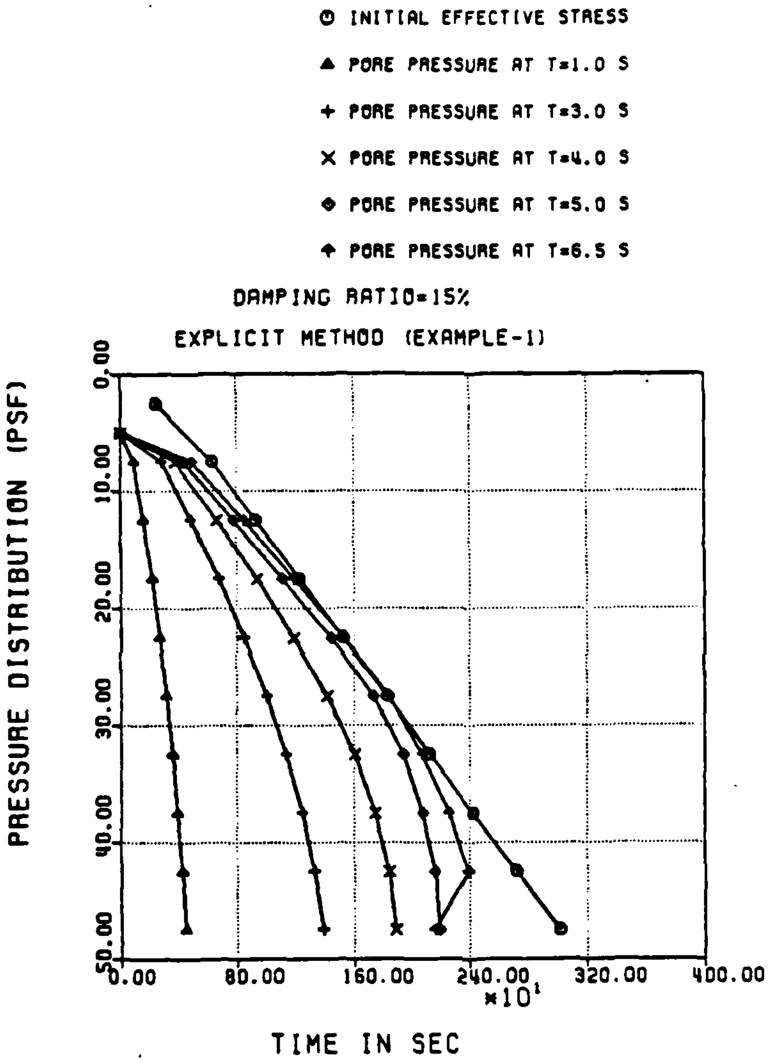

Figure 20: Example-1 Pressure Distribution (ξ = 0.15)

TABLE 2

Example-1 Time and Location of Liquefaction

Damping ratio or coefficient	Explicit Method		Implicit Method	
	Layer	Time (sec)	Layer	Time (sec)
$\xi = 0.02$	5,6,7,8	3.0	6	5.0
$\xi = 0.10$	6	4.0	No liquefaction	
$a_1 = 0.02$	5,6	5.0	-do-	
$\xi = 0.15$	5,6	6.5	.....	

TABLE 3

Example-1 Pressure Distribution (ξ = 0.02)

(Explicit Method)

Depth (feet)	Initial Effective Stress (psf)	Pore Pressure at Time 1.0 (sec)	1.5 (sec)	2.0 (sec)	2.5 (sec)	3.0 (sec)
5.0	239.30	0.0	0.0	0.0	0.0	0.0
7.5	627.60	109.7	181.7	265.4	378.0	443.8
12.5	925.60	186.2	309.5	458.2	668.0	808.5
17.5	1223.60	254.8	425.4	636.6	948.0	1209.6
22.5	1521.60	316.6	530.0	799.2	1211.5	1633.4
27.5	1819.60	371.5	622.4	943.0	1447.0	2021.2
32.5	2117.6	419.4	701.8	1065.1	1642.5	2303.8
37.5	2415.6	460.0	767.8	1163.5	1789.4	2452.7
42.5	2713.6	493.0	820.6	1237.7	1884.5	2492.0
47.5	3011.6	520.0	860.3	1288.0	1929.2	2458.9

TABLE 4

Example-1 Pressure Distribution (ξ = 0.02)

(Implicit Method)

Depth (feet)	Initial Effective Stress (psf)	Pore Pressure at Time				
		1.0 (sec)	2.0 (sec)	3.0 (sec)	4.0 (sec)	5.0 (sec)
5.0	239.30	0.0	0.0	0.0	0.0	0.0
7.5	627.60	53.4	116.8	191.8	291.0	336.3
12.5	925.60	90.7	200.8	336.1	529.3	623.7
17.5	1223.60	124.1	277.9	473.5	795.5	1008.0
22.5	1521.60	154.3	348.3	602.7	1092.7	1507.4
27.5	1819.60	181.3	411.0	719.9	1391.0	1856.9
32.5	2117.60	204.9	465.3	820.7	1628.5	2083.5
37.5	2415.60	225.1	510.4	901.5	1772.4	2233.0
42.5	2713.60	241.9	545.9	960.0	1823.2	2304.6
47.5	3011.60	255.6	566.9	984.4	1772.7	2238.3

TABLE 5

Example-1 Pressure Distribution ($\xi = 0.10$)

(Explicit Method)

Depth (feet)	Initial Effective Stress (psf)	Pore Pressure at Time				
		1.0 (sec)	1.5 (sec)	2.0 (sec)	3.0 (sec)	4.0 (sec)
5.0	239.30	0.0	0.0	0.0	0.0	0.0
7.5	627.60	97.7	153.8	209.6	341.6	431.2
12.5	925.60	167.7	263.7	361.2	600.2	771.9
17.5	1223.60	229.7	362.7	499.7	845.8	1131.6
22.5	1521.60	285.7	452.4	625.6	1073.8	1507.6
27.5	1819.60	335.6	535.1	737.6	1276.0	1850.7
32.5	2117.60	379.7	601.6	834.3	1445.0	2093.0
37.5	2415.60	417.5	660.6	914.8	1575.1	2213.2
42.5	2713.60	449.2	708.4	978.4	1667.3	2253.0
47.5	3011.60	474.9	745.4	1025.6	1716.4	2252.9

TABLE 6

Example-1 Pressure Distribution (ξ = 0.10)

(Implicit Method)

Depth (feet)	Initial Effective Stress (psf)	Pore Pressure at Time				
		2.0 (sec)	4.0 (sec)	6.0 (sec)	8.0 (sec)	10.0 (sec)
5.0	239.30	0.0	0.0	0.0	0.0	0.0
7.5	627.60	97.4	197.7	308.2	377.5	452.0
12.5	925.60	167.7	346.0	553.9	671.1	781.5
17.5	1223.60	231.7	485.3	803.4	965.0	1102.4
22.5	1521.60	290.0	615.2	1070.4	1277.6	1433.3
27.5	1819.60	342.2	732.7	1355.1	1619.4	1783.7
32.5	2117.6	387.9	834.0	1596.0	1907.2	2093.8
37.5	2415.6	426.6	916.1	1727.5	2039.8	2286.4
42.5	2713.6	458.1	977.2	1748.8	2078.1	2408.0
47.5	3011.60	477.9	1002.3	1684.1	2020.6	2411.1

TABLE 7

Example-1 Pressure Distribution (a_1 = 0.02)

(Explicit Method)

Depth (feet)	Initial Effective Stress (psf)	Pore Pressure at Time				
		1.0 (sec)	2.0 (sec)	3.0 (sec)	4.0 (sec)	5.0 (sec)
5.0	239.30	0.0	0.0	0.0	0.0	0.0
7.5	627.60	82.8	171.5	264.4	372.4	447.1
12.5	925.6	144.1	296.4	459.5	658.8	801.7
17.5	1223.60	199.3	410.3	639.6	933.4	1174.9
22.5	1521.60	248.7	513.6	804.1	1190.3	1564.7
27.5	1819.60	292.9	605.8	950.7	1418.0	1903.6
32.5	2117.60	332.1	686.9	1077.1	1605.3	2106.4
37.5	2415.60	366.4	756.1	1181.5	1745.4	2187.9
42.5	2713.60	395.7	813.0	1263.5	1837.9	2210.9
47.5	3011.60	420.0	857.0	1321.4	1886.6	2235.0

TABLE 8

Example-1 Pressure Distribution (a_1 = 0.02)

(Implicit Method)

Depth (feet)	Initial Effective Stress (psf)	Pore Pressure at Time 2.0 (sec)	4.0 (sec)	6.0 (sec)	8.0 (sec)	10.0 (sec)
5.0	239.30	0.0	0.0	0.0	0.0	0.0
7.5	627.60	81.2	152.8	236.4	329.7	400.5
12.5	925.60	140.5	265.4	414.8	588.2	704.9
17.5	1225.60	194.3	368.6	581.3	846.2	1005.4
22.5	1521.60	243.2	463.3	736.4	1109.5	1313.6
27.5	1819.60	287.1	548.5	876.2	1364.6	1621.0
32.5	2117.60	326.0	623.2	996.5	1569.3	1864.2
37.5	2415.60	359.5	686.4	1094.0	1687.5	1977.5
42.5	2713.60	387.7	737.6	1167.1	1731.0	2059.1
47.5	3011.60	406.6	784.0	1191.0	1697.5	2037.8

TABLE 9

Example-1 Pressure Distribution (ξ = 0.15)

(Explicit Method)

Depth (feet)	Initial Effective Stress (psf)	Pore Pressure at Time				
		1.0 (sec)	3.0 (sec)	4.0 (sec)	5.0 (sec)	6.5 (sec)
5.0	239.30	0.0	0.0	0.0	0.0	0.0
7.5	627.60	89.5	278.1	372.5	435.0	489.6
12.5	925.60	154.6	483.4	658.3	771.2	844.1
17.5	1223.60	212.6	673.4	932.1	1107.0	1187.0
22.5	1521.60	264.6	847.3	1188.4	1438.7	1528.2
27.5	1819.60	311.2	1002.3	1415.3	1728.4	1833.7
32.5	2117.60	352.4	1135.4	1601.3	1934.0	2062.2
37.5	2415.60	388.1	1244.3	1740.0	2069.3	2250.1
42.5	2713.60	418.3	1328.2	1831.9	2150.5	2385.0
47.5	3011.60	443.6	1386.4	1879.3	2187.4	2150.0

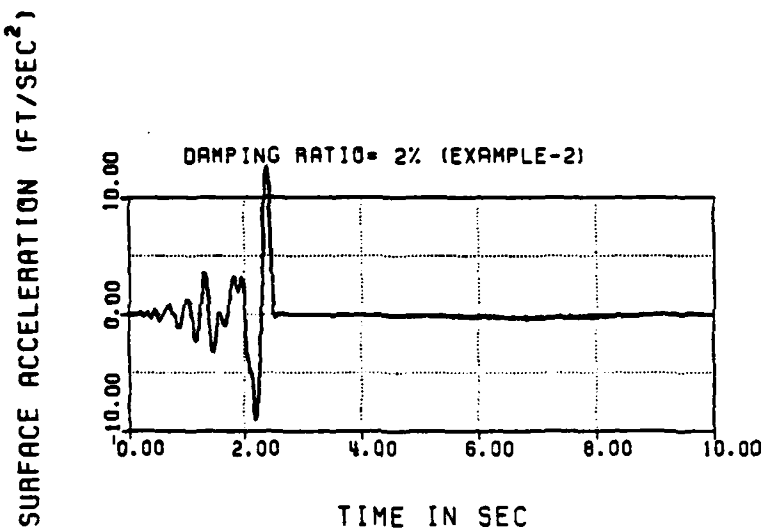

Figure 21: Example-2 Surface Acceleration (ξ = 0.02)

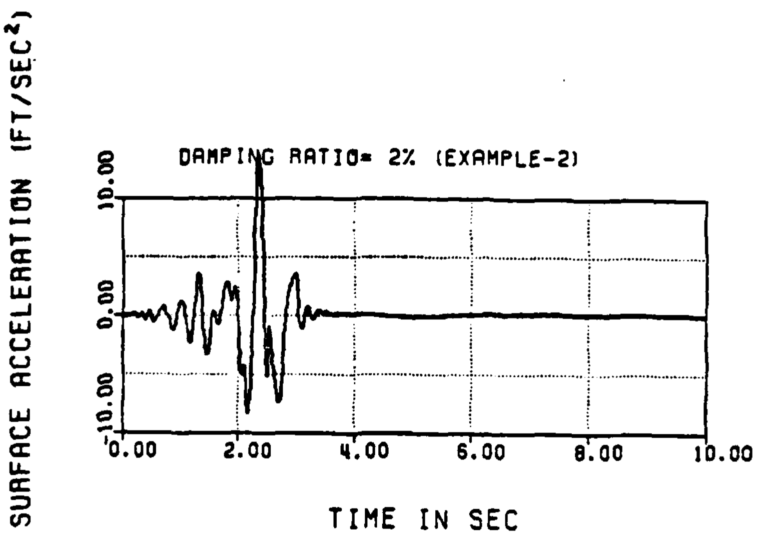

Figure 22: Example-2 Surface Acceleration (ξ = 0.02)

The shear stress variation for the layer that liquefied first is shown in Figure (23) for the Explicit method and in Figure (24) for the implicit method. The pore pressure distribution is shown in Figures (25) and (26) for the explicit and the implicit method respectively. Tables (10) and (11) list the pore pressure values.

4.3 SOME OBSERVATIONS

4.3.1 Example-1

The variation of surface acceleration over the period of excitation shown in Figures (10) and (11) indicated that the surface acceleration gradually built up and reached its maximum. After this, it dropped rapidly till liquefaction, when it reached near zero values. The shear stress variation in layer No. 6, which liquefied first, showed that the shear stress also increased initially till it reached its peak and then reduced sharply and attained near zero values at liquefaction. Figures (14) through (20) indicate that the pore pressure increased slowly in the initial stages of excitation. However, a stage is reached at which its value became equal to that of the initial effective stress. That point gives the liquefaction time and location.

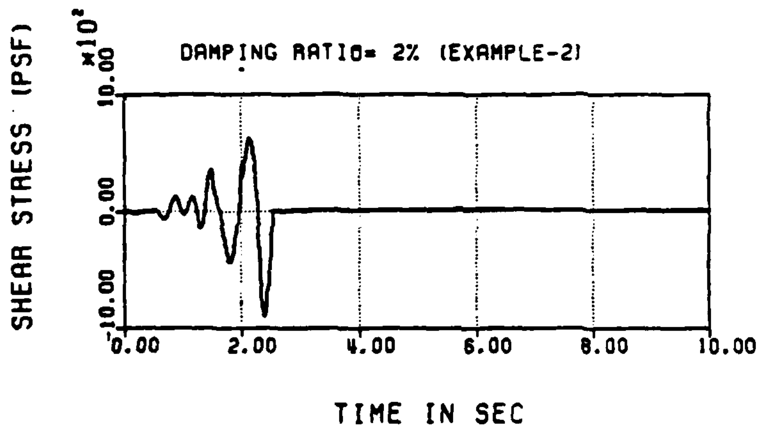

Figure 23: Example-2 Shear Stress (ξ = 0.02)

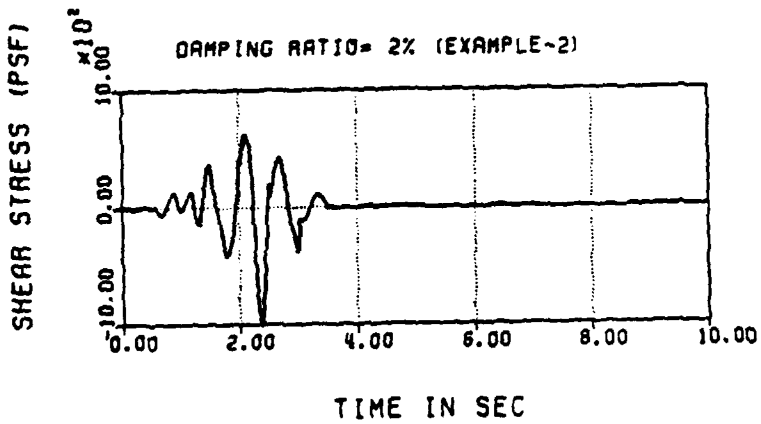

Figure 24: Example-2 Shear Stress (ξ = 0.02)

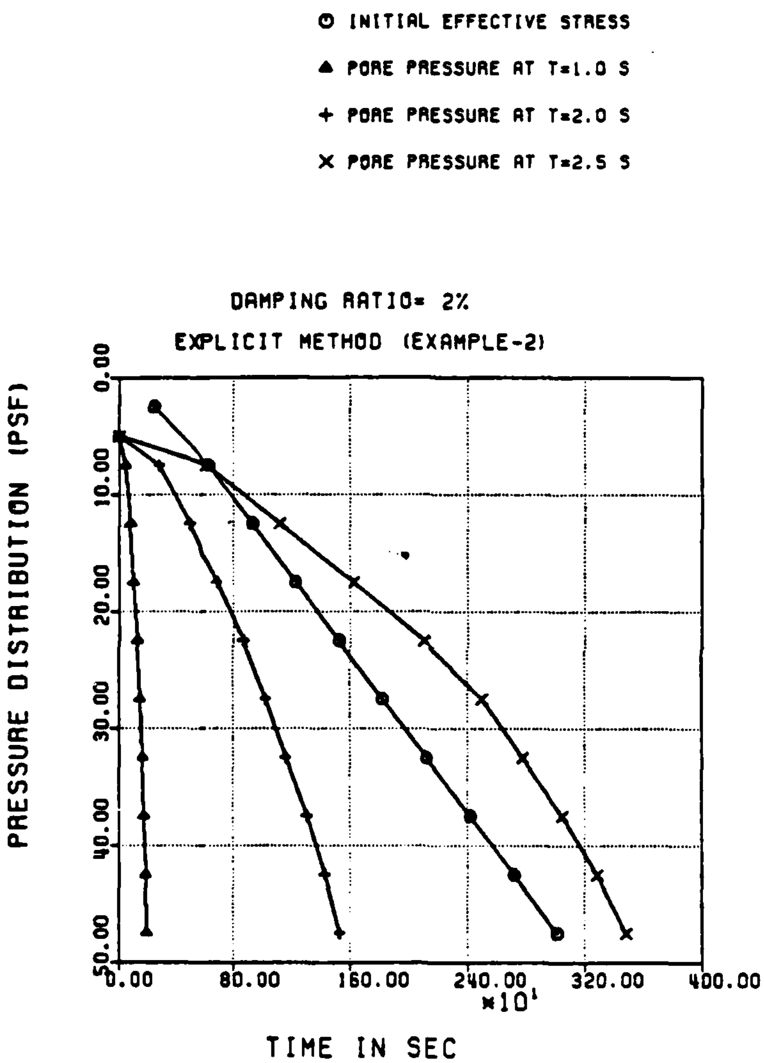

Figure 25: Example-2 Pressure Distribution (ξ = 0.02)

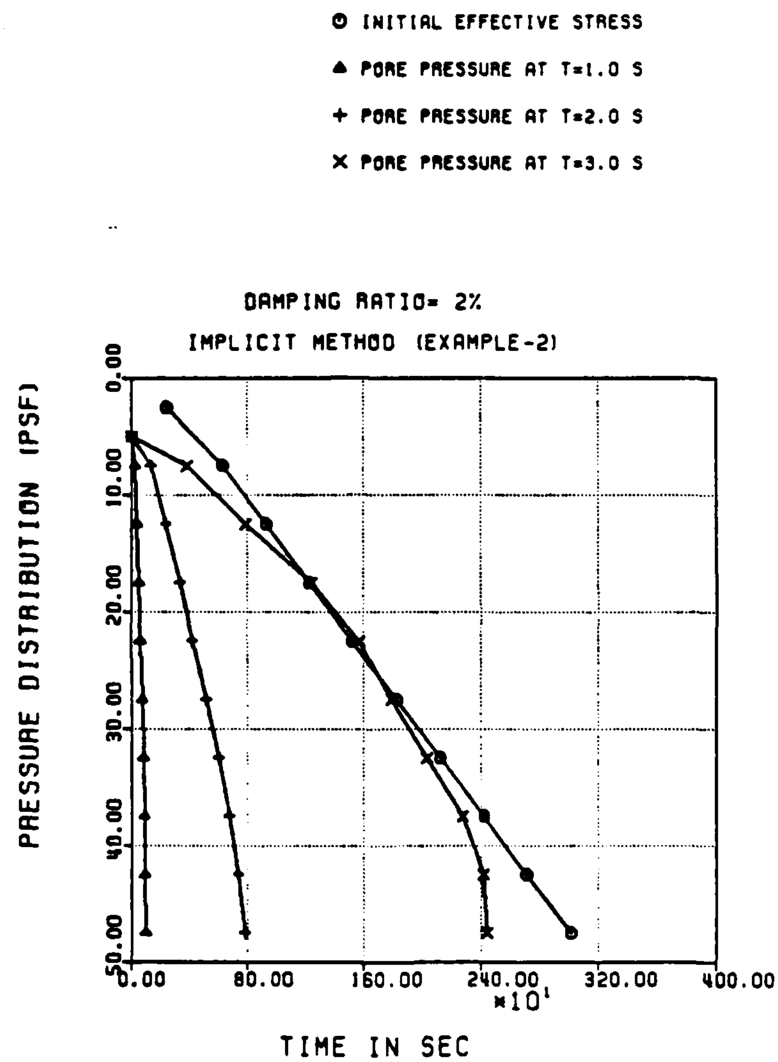

Figure 26: Example-2 Pressure Distribution (ξ = 0.02)

TABLE 10

Example-2 Pressure Distribution (ξ = 0.02)

(Explicit Method)

Depth (feet)	Initial Effective Stress (psf)	Pore Pressure at 1.0 (sec)	2.0 (sec)	3.0 (sec)
5.0	239.30	0.0	0.0	0.0
7.5	627.60	43.29	276.1	611.2
12.5	925.60	72.79	487.0	1114.0
17.5	1223.60	99.00	684.4	1623.4
22.5	1521.60	121.40	864.7	2100.8
27.5	1819.60	140.40	1022.7	2493.1
32.5	2117.60	156.40	1157.0	2772.9
37.5	2415.60	168.6	1304.9	3046.5
42.5	2713.60	177.50	1428.2	3278.6
47.5	3011.60	184.80	1529.0	3460.6

TABLE 11

Example-2 Pressure Distribution (ξ = 0.02)

(Implicit Method)

Depth (feet)	Initial Effective Stress (psf)	Pore Pressure at 1.0 (sec)	2.0 (sec)	3.0 (sec)
5.0	239.30	0.0	0.0	0.0
7.5	627.60	21.60	133.9	378.9
12.5	925.60	36.40	236.1	786.3
17.5	1223.60	49.50	331.6	1243.1
22.5	1521.60	60.60	419.2	1565.6
27.5	1819.60	70.10	512.2	1787.4
32.5	2117.60	78.10	598.8	2026.8
37.5	2415.60	84.20	673.4	2270.5
42.5	2713.60	88.70	735.6	2413.0
47.5	3011.60	92.00	781.8	2438.2

4.3.2 Example-2

The acceleration variation in Figures (21) and (22) show that surface acceleration reached values of more than 10.0 ft/second . The shear stress variation in Figures (23) and (24) shows that the maximum values of shear stress were near about 1000.0 psf. The pressure variation in Figures (25) and (26) indicates the effect of pore pressure build-up. The liquefaction occured at 2.5 and 3.0 seconds respectively in the explicit and the implicit method.

4.4 Influence of Damping Ratio

As seen in Figures (14) through (20), increase in the damping ratio, delayed the liquefaction. In fact, the time for liquefaction for $\xi = 0.15$ is more than twice that of the time with $\xi = 0.02$. The values of the maximum acceleration and shear stress also decreased with the increase in the damping ratio. Thus, choice of damping ratio influenced the overall response of the system to dynamic excitation significantly.

4.5 CHOICE OF DAMPING COEFFICIENT (a_1)

In Example-1, the stiffness proportional damping was used by taking the value of the damping coefficient to be

0.02 for the entire period of excitation. This was felt necessary to check the influence of the value of the natural frequency over the results. As was observed, while the time for liquefaction increased considerably for the explicit method, in the implicit method of analysis liquefaction did not occur at all. The values of the maximum acceleration and shear stress were found to lie between those given by the analysis with $\xi = 0.10$ and $\xi = 0.15$.

4.6 COMPARISON OF RESULTS WITH FINN [6]

Finn [6] presented results of his analysis for the case of damping ratio equal to 0.02. For this case, the results from the implicit method, which is expected to give more accurate results than the explicit method, were compared with those given by Finn [6]. Table (12) shows the values of the maximum acceleration, maximum shear stress, time of liquefaction and the depth at which the liquefaction occured first obtained using the implicit method in comparison with Finn's [6] results.

It is noted that the time of liquefaction differs widely from that of Finn [6], but the depth of liquefaction is the same in both the examples. Also, the values of the maximum acceleration and shear stress are significantly different.

TABLE 12

Comparison of Results with Finn [6]

	Implicit Method		Finn's Analysis	
	Example 1	Example 2	Example 1	Example 2
Maximum Acceleration	5.0	5.2	3.0	13.0
Maximum Shear Stress	500.0	1020.0	250.0	400.0
Time of Liquefaction	5.0	3.0	6.0	5.0
Depth	27.5	22.5	27.5	22.5

* Units used:

Acceleration : ft/second^2

Shear Stress : psf

Time : seconds

Depth : ft.

SECTION V

CONCLUSIONS

Numerical examples using computer program "SAND" based on the 'engineering approach' indicate the following:

1. The explicit method and implicit method give different results for the same time step. However, use of smaller time step for explicit to establish convergence to results obtained using the implicit method could not be done, since the choice of time step is dependent upon the frequency of input excitation and cannot be arbitrarily reduced.

2. The comparison of results from the implicit method with those reported by Finn [6] shows a wide difference in the values of maximum surface acceleration and shear stress. This could be due to one or more of the following reasons:

   a) Finn [6] has not indicated how the natural frequency of the system was established. This is essential to calculate the constant a in Equation (24). Since for stiffness proportional damping, the damping ratio is directly proportional to the natural frequency, this factor could be quite significant.

b) The expression for updated values of the shear modulus was not same as that used by Finn [6]. In this study, shear modulus is calculated using Equation (15) while Finn [6] had based it on Equations (4), (6) and (7). The values of constants used in these equations are not available.

c) The method of analysis for solution of diffusion equation is not mentioned by Finn [6]. In this study, both the explicit and the implicit methods were used. This part of establishing values of pore pressures is very important in this type of analysis, since the updated values of effective stresses are based on pore pressure distribution.

This study brought forth following drawbacks of the 'engineering approach' viz.

1. The method is based on simplifying assumptions such as the sequence of events listed in SECTION II, which is only an approximate representation of the physical phenomenon. In reality, the variation of pore pressure and soil properties is more likely to occur simultaneously and a correct theory must simulate that. For an approximate theory to be acceptable, its limits and validity must be carefully determined.

2. The method requires a large amount of input information in terms of soil properties and has several re-

lations based on experimental analysis. Without such information, the method cannot possibly predict the time and depth of liquefacton of soil stratum. These data are site specific and would be expensive to get.

3. The pore pressure is established using Equation (10) for calculating change in volumetric strain and Equation (14). Equation (10) is however based on experimental data. Since this is an important factor towards establishing soil properties in successive stages of excitation, this requires to be carefully studied.
4. The method is established for the case of horizontally layered soil strata only and the properties are assumed to vary only in the vertical direction. This places a serious restriction on the use of this method.
5. The soil properties are modified by updating the values of shear modulus. The basis for this updating needs to be examined, since this is related to the cost of computer program. The method is found to be expensive from this point of view.
6. The study established that the results of the program are dependent on the method of analysis. Also the time step for solution of diffusion equation is based on the frequency of the input excitation. Since this

is related to establishing other soil properties, it is not possible to set up a sequence of solutions with systematically decreasing time step size, to establish convergence to a unique result.

SECTION VI

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Appendix A

PROGRAM STRUCTURE AND ORGANIZATION

A.1 INTRODUCTION

The computer program consists of a main unit and several subroutines. Figure (A.1) shows the nesting of subroutines.

A.2 MAIN

In this unit, the control information is read in. The dynamic storage allocation is set up and locations of various arrays specified.

A.3 INPT

This subroutine is called by the unit MAIN. In this subroutine, the dynamic storage allocation is completed and storage requirement for problem under consideration is checked. This subroutine also forms the main body of the program and calls in various subroutines for specific operations.

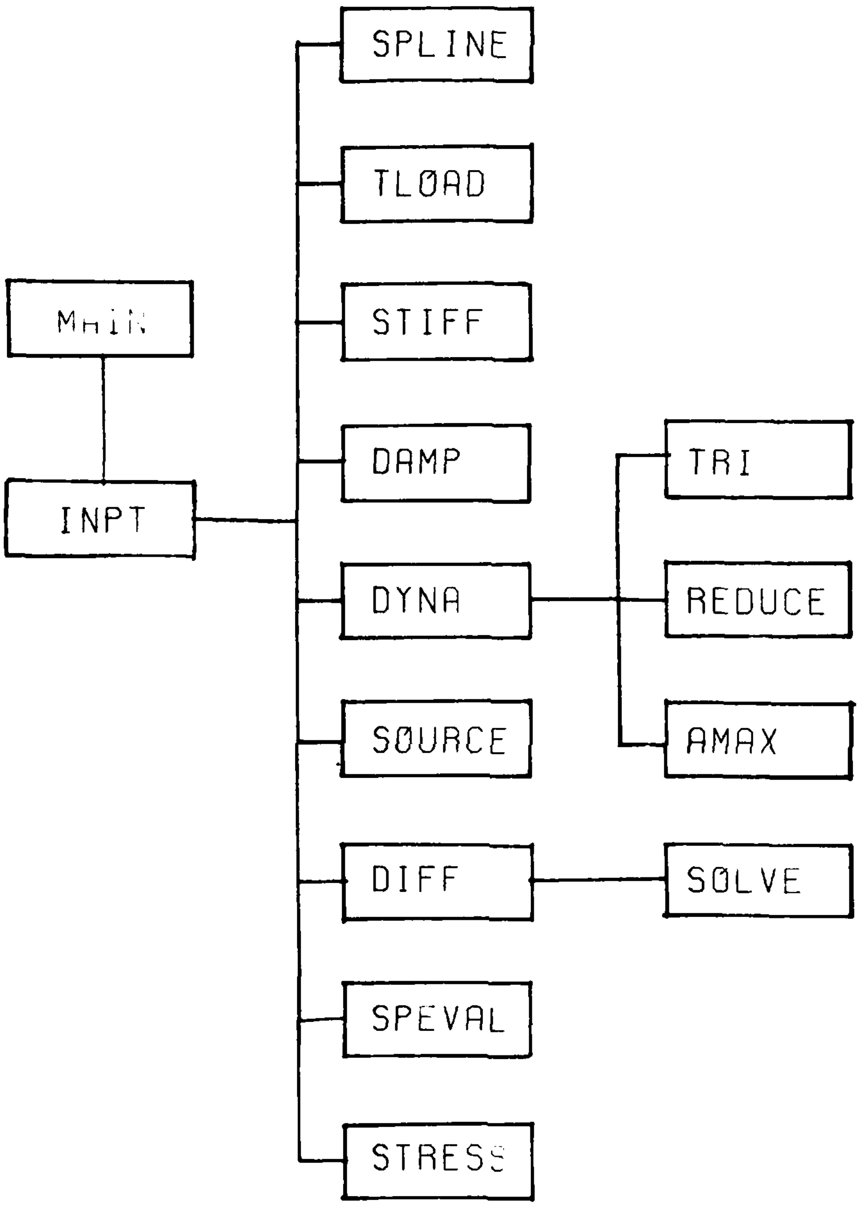

Figure A.27: Nesting of Subroutines

A.4 SPLINE

This subroutine is called by the unit INPT. In this subroutine, the spline interpolation of the data points is carried out.

A.5 TLOAD

This subroutine, called by the unit INPT, sets up the load vector in the dynamic equation of motion, based on the input base excitation. While the values of the acceleration for harmonic excitation are evaluated, the values for other type of excitation are to be read in. The choice is to be indicated by using ICOUNT = 1 for harmonic base input and ICOUNT = 1 for other types. The input frequency for harmonic excitation is to be expressed as a multiple of = 3.1415927 and this multiple is indicated in form of the variable ANOMEG.

A.6 STIFF

This subroutine is called by the unit INPT and sets up the system stiffness matrix for every cycle of periodic updating of soil properties.

A.7 DAMP

This subroutine as also called by the INPT unit and sets up the system damping matrix for periodic updates.

A.8 DYNA

This subroutine is called by the unit INPT for solving the dynamic equation of motion and gives displacements, velocities and accelerations. The shear strains are also evaluated by this subroutine.

A.9 SOURCE

This subroutine is called by the unit INPT and calculates the source term in the diffusion equation expressed as function of change of volumetric strain.

A.10 DIFF

This subroutine, called by INPT, solves the diffusion equation using both the explicit and implicit method. This is achieved by using IFLAG = 1 for the explicit method and IFLAG = 1 for the implicit method.

A.11 SPEVAL

This subroutine, called by the unit INPT, calculates the interpolated value using spline interpolation already established in SPLINE.

A.12 STRESS

This subroutine is called by INPT and evaluates the pore pressure and effective stresses at the end of each cycle of periodic update.

A.13 TRI

This subroutine, called by the subroutine DYNA, performs standard Gaussian elimination on the coefficient matrix of a system of linear equations. No pivoting is used. It reduces the matrix to triangular form.

A.14 REDUCE

This subroutine is called by the subroutine DYNA for row operations on the vector in a system of linear equations and carries out back-substitution to evaluate the unknown displacements.

AD-A150 769 A COMPUTER PROGRAM FOR DYNAMIC RESPONSE OF LAYERED SATURATED SANDS..(U) OHIO STATE UNIV RESEARCH FOUNDATION COLUMBUS M S HIREMATH ET AL. JUN 84 2/2

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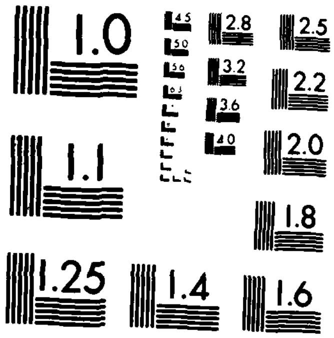

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A.15 AMAX

This subroutine is called by the subroutine DYNA to calculate the maximum shear strain for the cycle of periodic update of soil properties.

A.16 SOLVE

This subroutine, called by the subroutine DIFF, solves tri-diagonal system of equations.

Appendix B

PROGRAM USAGE

B.1 PROGRAM IDENTIFICATION

Name: SAND

Programmer: M. S. Hiremath, Ohio State University, Columbus, Ohio.

Date: April 1984.

B.2 INPUT DATA

Input to the program is a sequence of punched cards in the following order and format.

B.2.1 Problem Identification (18A4)

One card carries a descriptive title to identify the job.

B.2.2 Control Information

These sets of cards will provide the following control information for the problem being solved.

i. First Card (4I10)

Information	Columns
Total number of layers (ND)	1 - 10
Number of dry layers (LAYDRY)	11 - 20
Number of data points (NN)	21 - 30
(Used in interpolation of curve in Figure (2)).	
Number of spatial divisions (N)	31 - 40

ii. Second Card (8F10.0)

Information	Columns
Depth of sand system (Z)	1 - 10
Acceleration due to gravity (EG)	11 - 20
Damping ratio (ZETA)	21 - 30
Unit weight of saturated sand (GAMSAT)	31 - 40
Unit weight of water (GAMW)	41 - 50
Specific gravity of sand (SPGRA)	51 - 60
Angle of shear resistance (PHI)	61 - 70
Relative density (RELDEN)	71 - 80

iii. Third Card (10F5.0)

Information	Columns
Values of shear strain in Figure (2)	1 - 50
(In all NN values are to be provided one value for in every five columns)	
Array is denoted by (X).	

iv. Fourth Card (10f5.0)

Information	Columns
Values of K in Figure (2) corresponding to the values in array (X). NN values are to be provided, one in every five columns. The Array is denoted by (Y)	1-50

v. Fifth Card (3F10.0)

Information	Columns
Value of 'm' in Equation (11) (AM)...	1 - 10
Value of 'n' in Equation (11) (AN)...	11 - 20
Value of 'k' in Equation (11) (AK)...	21 - 30

vi. Sixth Card (F10.0)

Information	Columns
Initial shear strain (SSTI)	1 - 10

vii. Seventh Card (4F10.0)

Information	Columns
Permeability of sand system (PERM) ..	1 - 10
Depth of saturated portion (XL)	11 - 20
Time step for updating properties (D)	21 - 30
Total time period of excitation (TMAX)	31 - 40

viii. Eighth Card (i10)

Information	Columns
Number of divisions of TMAX	1 - 10

ix. Ninth Card (3F10.0)

Information	Columns
Multiple of 'π' in input frequency (ANOMEG)	1 - 10
Time step for calculating load (DELT).	11 - 20
Maximum Acceleration (AA)	21 - 30

x. Tenth Card (4F10.0)

Information	Columns
Time step for Newmark's method (TSTEP)	1 - 10
Newmark's constant (δ) (DELTA)	11 - 20
Newmark's constant (α) (ALPHA)	21 - 30
Time period for Newmark's method (TFIN)	31 - 40

xi. Eleventh Card (I10)

Information	Columns
Number of divisions of TFIN	1 - 10

B.2.3 Initial Value Data

Corresponding to each lumped mass, one card is to be provided, giving the value of initial displacement and initial velocity.

Information	Columns
Initial Displacement (UDI(ND))	1 - 10
Initial velocity (UVI(ND))	11 - 20

B.2.4 Soil Constants

Soil constants in Equation (10) are to be supplied as follows.

Information	Columns
Value of C_1 (C1)	1 - 10
Value of C_2 (C2)	11 - 20
Value of C_3 (C3)	21 - 30
Value of C_4 (C4)	31 - 40

B.2.5 Choice of the Method

Choice of the method and type of base input is to be indicated using following two cards.

i. First Card (I10)

Information	Columns
IFLAG = 1 for Explicit method	1 - 10
= 2 for Implicit method	

ii. Second Card (I10)

Information	Columns
ICOUNT = 1 for harmonic base input	1 - 10
= 2 for other type of input	

Appendix C

DICTIONARY OF VARIABLE NAMES

Following is the list of variables used in the computer program SAND. The dimensions of the arrays are indicated and may be altered to suite the problem to be analysed.

VARIABLE	DESCRIPTION
AKO	Coefficient of earth pressure at rest.
AK2	Interpolated value of the coeffcient K
A, B, C	Diagonals in a tri-diagonal system.
A1	Stiffness damping coeffcient.
A(ND,ND)	Coefficient matrix in a set of linear equations.
A_1, thr A_7	Constants in NEWMARK'S method.
B(ND)	The known vector associated with a set of linear equations.
BETA(N)	Constant in explicit method.
BET(ND)	Value of the constant term in the explicit method associated with each sand layer.

CHVD(ND)	Change in the volumetric strain during the cycle under consideration.
DEN(ND)	Denominator in the expression for E
DELVD(ND)	Change in volumetric strain(=CHVD)
EE	Void ratio
ER(ND)	One-dimensional rebound modulus.
EER(N)	Value of E associated with each source term in the diffusion equation.
EPSVD(ND)	Cumulative volumetric strain for each layer.
ESTI(ND)	Effective stress for each layer.
EKI(ND)	Value of the spring constant for each layer.
F	Interpolated value of K_2.
FF(ND,NT+1)	Array for load vector in dynamic equation of motion for entire period of excitation.
FR(ND)	Values of the pore pressure in the diffusion equation.
FDP(NN)	Array containing second derivatives in interpolating cubic spline.
GAMDRY	Unit weight of dry sand.
GAMA(ND)	Unit weight of each sand layer.
GMO(ND)	Initial value of the shear modulus

	for each layer.
GI(ND)	Values of the shear modulus for each layer.
G(ND)	Duplicate of GI(ND).
H(ND)	Depth of each layer.
KKK	Counter for number of cycles.
PPI(ND)	Pore pressure at the center of each layer.
Q(N)	Source term in the diffusion equation.
R	Right hand side vector in tri-diagonal system in Subroutine SPLINE>
SM(ND,ND)	Mass matrix in Dynamic analysis.
SK(ND,ND)	Stiffness matrix in Dynamic analysis.
SC(ND,ND)	Damping matrix in Dynamic analysis.
SIGZER(ND)	Initial values of the shear stresses.
SST(ND)	Values of the shear strains.
SIGMAO(ND)	Mean normal effective stress for each layer.
SIGMAV(ND)	Net effective stress at the end of each cycle.
SHEAR(ND)	Shear stress in each layer.
SKK(ND)	Duplicate for EKI(ND)
TSTI(ND)	Initial total stress for each layer.

TMO(ND)	Value of the initial maximum shear stress for each layer.
T(N-1)	Temporary array in subroutine DIFF
UAI(ND)	Initial acceleration.
UD(ND)	Displacements of masses.
UV(ND)	Velocities of masses.
UA(ND)	Accelerations of masses.
WN	Natural frequency of the stratum.
XX	Value of the maximum shear strain for which interpolated value of K_2 is calculated in subroutine SPEVAL.
XL	Length of spatial domain in explicit method.
Y(ND)	Data points for cubic spline interpolation used for finding K_2.
Z	Total depth of sand stratum.
ZETA	Damping ratio.

Appendix D

PROGRAM LISTING

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CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C                                                         C
C     COMPUTER PROGRAM "SAND"                             C
C     ------------------------                            C
C                                                         C
C     FOR DYNAMIC RESPONSE OF FLUID SATURATED LAYERED     C
C     SAND STRATUM                                        C
C                                                         C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
      IMPLICIT REAL*8(A-H,O-Z)
      COMMON RA(18000)
      COMMON /AAA/ ND,LAYDRY,NN,N,NM
      COMMON /BBB/ NT,NDIV,NTP,NDIVP
      COMMON /CCC/ N36
C
      DIMENSION HEAD(18)
C
      READ (5,20) HEAD
C
      READ (5,30) ND,LAYDRY,NN,NLD
C
      READ (5,40) NT,NDIV
C
      N=NLD*(ND-LAYDRY)
      NM=N-1
      NTP=NT+1
      NDIVP=NDIV+1
C
      WRITE (6,50) HEAD,ND,LAYDRY,NN,NLD,N,NT,NDIV
C
      N1=1
      N2=N1+ND
      N3=N2+ND
      N4=N3+ND
      N5=N4+ND
      N6=N5+ND
      N7=N6+ND
      N8=N7+ND
      N9=N8+ND
      N10=N9+ND
      N11=N10+ND
```

```
      N12=N11+ND
      N13=N12+ND
      N14=N13+ND
      N15=N14+ND
      N16=N15+ND
      N17=N16+ND
      N18=N17+ND
      N19=N18+ND
      N20=N19+ND
      N21=N20+NN
      N22=N21+NN
      N23=N22+NN
      N24=N23+ND
      N25=N24+ND*ND
      N26=N25+ND*ND
      N27=N26+ND*ND
      N28=N27+ND
      N29=N28+ND
      N30=N29+ND
      N31=N30+ND*NTP
      N32=N31+N
      N33=N32+N
      N34=N33+N
      N35=N34+N
      N36=N35+ND
C
      CALL INPT (RA(N1),RA(N2),RA(N3),RA(N4),RA(N5),RA(N6),RA(N7),RA(N8)
     1,RA(N9),RA(N10),RA(N11),RA(N12),RA(N13),RA(N14),RA(N15),RA(N16),RA
     2(N17),RA(N18),RA(N19),RA(N20),RA(N21),RA(N22),RA(N23),RA(N24),RA(N
     325),RA(N26),RA(N27),RA(N28),RA(N29),RA(N30),RA(N31),RA(N32),RA(N33
     4),RA(N34),RA(N35))
C
      STOP
C
 20   FORMAT (18A4)
 30   FORMAT (4I5)
 40   FORMAT (2I5)
 50   FORMAT (1H1,//18A4//5X,'TOTAL NUMBER OF LAYERS
     1= ',I5/5X,'NUMBER OF DRY LAYERS                            = ',I5/5X,'NU
     2MBER OF DATA POINTS FOR INTERPOLATION    = ',I5/5X,'NUMBER OF DIVIS
     3IONS OF EACH LAYER          = ',I5/5X,'TOTAL NUMBER OF SPATIAL DIVI
     4SIONS          = ',I5/5X,'NUMBER OF DIVISIONS OF EXCITATION PERIOD
     5 = ',I5/5X,'NUMBER OF DIVISIONS OF EACH CYCLE PERIOD  = ',I5///)
      END
```

```
      SUBROUTINE INPT (H,GAMA,TSTI,PPI,ESTI,DEN,ER,GMO,TMO,GI,G,BIG,SIGM
C     ==================================================================
     1AV,SIGMAO,SSTR,SHEARM,CHVD,SIGZER,EKI,X,Y,FDP,AK2,SM,SK,SC,EPSVD,U
C     ==================================================================
     2DI,UVI,FF,Q,FR,BETA,EER,BET)
C     ===========================
C
      IMPLICIT REAL*8(A-H,O-Z)
      COMMON RA(18000)
      COMMON /AAA/ ND,LAYDRY,NN,N,NM
      COMMON /BBB/ NT,NDIV,NTP,NDIVP
      COMMON /CCC/ N36
      COMMON /ONE/ KKK
      COMMON /TWO/ ILIQ
      COMMON /THREE/ DELT,TMAX,AA,ANOMEG
      COMMON /FOUR/ TSTEP,DELTA,ALPHA,TFIN
      COMMON /FIVE/ C1,C2,C3,C4
C
      DIMENSION H(ND), GAMA(ND), TSTI(ND), PPI(ND), ESTI(ND), DEN(ND), E
     1R(ND), GMO(ND), TMO(ND), GI(ND), G(ND), BIG(ND), SIGMAV(ND), SIGMA
     2O(ND), SSTR(ND), SHEARM(ND), CHVD(ND), SIGZER(ND), EKI(ND), X(NN),
     3 Y(NN), FDP(NN)
      DIMENSION AK2(ND), Q(N), FR(N), BETA(N), EER(N), BET(ND), SM(ND,ND
     1), SK(ND,ND), SC(ND,ND), EPSVD(ND), UDI(ND), UVI(ND), FF(ND,NTP)
      N37=N36+NN
      N38=N37+NN
      N39=N38+NN
      N40=N39+NN
C
      N41=N40+NT
C
      N42=N41+ND
      N43=N42+ND
      N44=N43+ND
      N45=N44+ND
      N46=N45+ND
      N47=N46+ND*NDIVP
      N48=N47+ND
      N49=N48+ND*ND
      N50=N49+ND
      N51=N50+ND
      N52=N51+ND
C
      N53=N52+N
      N54=N53+N
      N55=N54+N
      N56=N55+N
      N57=N56+N
      N58=N57+N
C
      N59=N58+ND
C
```

```
      WRITE (6,300) N59
C
      NTOT=18000
      IF(N59.LE.NTOT) GO TO 10
      WRITE (6,310)
C
      CALL EXIT
C
 10   CONTINUE
C
      READ (5,320) Z,EG,ZETA,GAMSAT,GAMW,SPGRA,PHI,RELDEN
      WRITE (6,330) Z,EG,ZETA,GAMSAT,GAMW,SPGRA,PHI,RELDEN
C
      READ (5,340) (X(I),I=1,ND)
      WRITE (6,350) (X(I),I=1,ND)
C
      READ (5,360) (Y(I),I=1,ND)
      WRITE (6,370)
C
      READ (5,380) AM,AN,AK
      WRITE (6,390) AM,AN,AK
C
      READ (5,400) SSTI
      WRITE (6,410) SSTI
C
      READ (5,420) PERM,XL,DT,TMAX
      WRITE (6,430) PERM,XL,DT,TMAX
C
      READ (5,440) ANOMEG,DELT,AA
      WRITE (6,450) ANOMEG,DELT,AA
C
      READ (5,460) TSTEP,DELTA,ALPHA,TFIN
      WRITE (6,470) TSTEP,DELTA,ALPHA,TFIN
C
      DO 20 I=1,ND
      READ (5,480) UDI(I),UVI(I)
      WRITE (6,490) UDI(I),UVI(I)
 20   CONTINUE
C
      READ (5,500) C1,C2,C3,C4
      WRITE (6,510) C1,C2,C3,C4
C
      READ (5,520) IFLAG
      WRITE (6,520) IFLAG
C
      READ (5,530) ICOUNT
      WRITE (6,530) ICOUNT
C
C
      CALL SPLINE (NN,X,Y,FDP,RA(N36),RA(N37),RA(N38),RA(N39))
C     ================================
C
```

```
C     CALCULATE SOIL PROPERTIES AND PRINT THEM
C
      PI=4.*DATAN(1.D0)
      RAD=PHI*PI/180.
      AKO=1.0-DSIN(RAD)
      EE=(SPGRA*GAMW-GAMSAT)/(GAMSAT-GAMW)
      GAMDRY=(GAMSAT-GAMW)*SPGRA/(SPGRA-1.0)
C
C     NOTE : THE SAND LAYERS ARE NUMBERED FROM TOP
C     -----------------------------------------
C
      AND=ND
      HH=Z/AND
C
      DO 30 I=1,ND
      H(I)=HH
 30   CONTINUE
C
      DO 40 I=1,LAYDRY
 40   GAMA(I)=GAMDRY
C
      LAYDR1=LAYDRY+1
      DO 50 I=LAYDR1,ND
 50   GAMA(I)=GAMSAT
C
      LAYWET=ND-LAYDRY
      LAYER=(LAYWET+1)/2
      LAYMID=LAYDRY+LAYER
C
      GAMAC=GAMA(LAYMID)
C
C
      WRITE (6,540)
C
      WRITE (6,550) Z,EG,ZETA,GAMSAT,GAMW,SPGRA,PHI,AKO,EE,GAMDRY,HH,REL
     1DEN
C
      WRITE (6,560)
C
C     SET UP THE MASS MATRIX
C
      DO 60 I=1,ND
      DO 60 J=1,ND
      SM(I,J)=0.0
 60   CONTINUE
C
C     CALCULATE THE NONZERO ELEMENTS OF THE MATRIX
C
      SM(1,1)=GAMA(1)*H(1)*0.5/EG
C
      DO 70 I=2,ND
      SM(I,I)=(GAMA(I-1)*H(I-1)+GAMA(I)*H(I))*0.5/EG
```

```
 70   CONTINUE
C
C     CALCULATE THE TOTAL PRESSURE, PORE PRESSURE AND EFFECTIVE PRESSURE
C     AT THE CENTER OF EACH LAYER
C
      TSTI(1)=0.5*H(1)*GAMA(1)
      DO 80 I=2,ND
      TSTI(I)=TSTI(I-1)+0.5*(H(I)*GAMA(I)+H(I-1)*GAMA(I-1))
 80   CONTINUE
C
      PPI(1)=0.0
      PPI(2)=0.5*H(2)*GAMW
C
      DO 90 I=3,ND
      PPI(I)=PPI(I-1)+0.5*(H(I-1)+H(I))*GAMW
 90   CONTINUE
C
      DO 100 I=1,ND
      ESTI(I)=TSTI(I)-PPI(I)
 100  CONTINUE
C
C
C     DUPLICATE THE ARRAY ESTI
      DO 110 I=1,ND
      SIGZER(I)=ESTI(I)
 110  CONTINUE
C
      WRITE (6,570)
C
      WRITE (6,580) (TSTI(I),ESTI(I),PPI(I),I=1,ND)
C
C
C     CALCULATE DENOMINATOR IN EXPRESSION FOR ER
      ANM=AN-AM
      AM1=1.-AM
      DO 120 I=1,ND
      DEN(I)=AM*AK*(ESTI(I)**ANM)
 120  CONTINUE
C
C
C     CALCULATE GMO AND TMO AT THE CENTRE OF EACH LAYER
      FAC1=((2.973-EE)**2)/(1.+EE)
      FAC2=DSQRT((1.+2.*AKO)/3.0)
C
      DO 130 I=1,ND
      GMO(I)=14760.0*FAC1*FAC2*DSQRT(ESTI(I))
 130  CONTINUE
C
      FAC3=((1.+AKO)*0.5*DSIN(RAD))**2
      FAC4=((1.-AKO)*0.5)**2
      FAC5=FAC3-FAC4
C
```

```
      DO 140 I=1,ND
      TMO(I)=DSQRT(FAC5)*ESTI(I)
 140  CONTINUE
C
      CALL TLOAD (NTP,FF,NT,ND,SM,ICOUNT,RA(N40))
C     ================================================
C
      DO 150 I=1,ND
      GI(I)=GMO(I)/(1.0+GMO(I)*SSTI/TMO(I))
 150  CONTINUE
      GMID=GI(LAYMID)
C
      DO 160 I=2,N
      FR(I)=0.0
 160  CONTINUE
C
C     INITIALISE THE CUMULATIVE VOLUMETRIC STRAIN.
C
      DO 170 I=1,ND
      EPSVD(I)=0.0
 170  CONTINUE
C
C     START OF THE BIG LOOP WHICH INVOLVES SOLVING OF DYNAMIC EQUATION
C     OF MOTION AND DIFFUSION EQUATION AND SUBSEQUENT UPDATING OF THE
C     STIFFNESS MATRIX ETC.
C
C     INITIALISE THE COUNTERS
C
      T=0.0
      ILIQ=0
      KKK=1
 180  CONTINUE
C
      WRITE (6,590) KKK
C
      WRITE (6,600) ZETA,ILIQ
C
      WRITE (6,610)
C
      DO 190 I=1,ND
      EKI(I)=GI(I)/H(I)
 190  CONTINUE
C
      CALL STIFF (EKI,ND,SK)
C     ===========================
C
      DO 200 I=1,ND
      G(I)=GI(I)
 200  CONTINUE
C
C     CALCULATE THE FUNDAMENTAL FREQUENCY OF THE SIXTH LAYER OF THE
C     STRATA SINCE IT LIES AT THE MIDDLE OF THE SAND STRATUM
```

```
C
      ZH=(Z-HH)*0.5
      ZH=ZH**0.3333
      AW=G(LAYMID)/ZH
C
      WN=1.7510*DSQRT(AW*EG/GAMAC)/(1.2*(Z-HH)**0.83333)
C
      CALL DAMP (WN,ZETA,ND,SK,SC)
C     ================================
C
      CALL DYNA(BIG,SM,SK,SC,FF,GI,H,UDI,UVI,
C     ================================================================
     *          RA(N41),RA(N42),RA(N43),RA(N44),RA(N45),RA(N46),
C               ===================================================
     *          RA(N47),RA(N48),RA(N49),RA(N50))
C               ================================
C
      DO 210 I=1,ND
      SHEARM(I)=GI(I)*BIG(I)
 210  CONTINUE
      CALL SOURCE (ND,KKK,CHVD,EPSVD,BIG,RA(N51))
C     ============================
C
C     CONVERT SHEAR STRAINS INTO PERCENTAGES
C
      DO 220 I=1,ND
      SSTR(I)=100.*BIG(I)
      IF(SSTR(I).GT.1.0) SSTR(I)=1.0
      IF(SSTR(I).LT.0.0001) SSTR(I)=0.0001
 220  CONTINUE
C
C     EVALUATE THE VALUES OF ELASTIC REBOUND MODULUS
C     FOR EACH LAYER
C
      DO 230 I=1,ND
      ER(I)=(ESTI(I)**AM1)/DEN(I)
 230  CONTINUE
C
C     EVALUATE THE CONSTANT TERM "BETA" FOR EACH LAYER
C
      AN=N
      DX=XL/AN
      DO 240 I=1,ND
      BET(I)=ER(I)*PERM*DT/(GAMW*DX*DX)
 240  CONTINUE
C
C
      NM1=N-1
      NND=ND
      DO 250 I=2,N,2
      Q(I)=CHVD(NND)
      EER(I)=ER(NND)
```

```
      BETA(I)=BET(NND)
      NND=NND-1
  250 CONTINUE
C
C     COMPLETE THE OTHER ELEMENTS OF Q, ER, BETA
C
      DO 260 I=3,NM1,2
      Q(I)=(Q(I-1)+Q(I+1))*0.5
      EER(I)=(EER(I-1)+EER(I+1))*0.5
      BETA(I)=(BETA(I-1)+BETA(I+1))*0.5
  260 CONTINUE
C
      DO 270 I=2,N
  270 Q(I)=EER(I)*Q(I)*100.0
C
      CALL DIFF (IFLAG,N,FR,Q,BETA,NM,RA(N52),RA(N53),RA(N54),RA(N55),RA
     1(N56),RA(N57))
C     ================================================================
C
C     CALCULATE THE VALUE OF K2 FOR EACH LAYER BY INTERPOLATION
C
      DO 280 I=1,ND
      XX=SSTR(I)
C
      CALL SPEVAL (NN,X,Y,FDP,XX,F)
C     =================================
C
      AK2(I)=F
  280 CONTINUE
C
      CALL STRESS (ND,N,CHVD,DT,ESTI,FR,SIGMAO,SIGMAV,SIGZER,AKO,RA(N58)
     1)
C     ================================================================
C
      DO 290 I=1,ND
      GI(I)=1000.*AK2(I)*DSQRT(SIGMAO(I))
  290 CONTINUE
C
      T=DT*KKK
      KKK=KKK+1
C
      IF(T.LT.TMAX) GO TO 180
C
      STOP
C
  300 FORMAT (//5X,'TOTAL STORAGE USED FOR THIS PROBLEM = ',I10//)
  310 FORMAT (1H1,///10X,'STORAGE EXCEEDED',//)
  320 FORMAT (8F10.0)
  330 FORMAT (8F10.4)
  340 FORMAT (10F5.0)
  350 FORMAT (3X,F7.4,F7.3,8F7.3)
  360 FORMAT (10F5.0)
```

```
370  FORMAT (10F5.1)
380  FORMAT (3F10.0)
390  FORMAT (3F10.4)
400  FORMAT (F10.0)
410  FORMAT (F10.4)
420  FORMAT (4F10.0)
430  FORMAT (4F10.4)
440  FORMAT (F10.0,2F10.0)
450  FORMAT (F10.4,2F10.4)
460  FORMAT (4F10.0)
470  FORMAT (4F10.4)
480  FORMAT (2F10.0)
490  FORMAT (2F10.4)
500  FORMAT (4F10.0)
510  FORMAT (4F10.4)
520  FORMAT (I10)
530  FORMAT (I10)
540  FORMAT (1H1,///15X,'SOIL PROPERTIES ARE',///)
550  FORMAT (5X,'TOTAL DEPTH OF SAND STRATA          =',F15.4/5X,'ACCELE
    1RATION DUE TO GRAVITY        =',F15.4/5X,'DAMPING COEFFICIENT
    2           =',F15.4/5X,'UNIT WEIGHT OF SATURATED SAND      =',F15.
    34/5X,'UNIT WEIGHT OF WATER                  =',F15.4/5X,'SPECIFIC GRA
    4VITY OF SAND             =',F15.4/5X,'ANGLE OF FRICTION
    5     =',F15.4/5X,'COEFFICIENT OF EARTH PRESSURE      =',F15.4/5X,'
    6VOID RATIO                             =',F15.4/5X,'UNIT WEIGHT OF DRY
    7 SAND             =',F15.4/5X,'HEIGHT OF EACH LAYER                =
    8',F15.4/5X,'RELATIVE DENSITY OF SAND            =',F15.4///)
560  FORMAT (1H1)
570  FORMAT (//,15X,'AT TIME T=0.0 SEC'//3X,'TOTAL STRESS',3X,'EFFECTIV
    1ESTRESS',3X,'PORE PRESSURE',//)
580  FORMAT (3(2X,F15.4))
590  FORMAT (1H1,21X,'CYCLE NUMBER IS',I5,/24X,'--------------',/)
600  FORMAT (10X,'DAMPING RATIO = ',F10.5/,10X,'LAYER FIRST TO LIQUEFY
    1= ',I5,/)
610  FORMAT (2X,'TIME',8X,'SHEAR(2)',2X,'SHEAR(3)',2X,'SHEAR(4)',2X,'SH
    1EAR(5)',2X,'SHEAR(6)',2X,'SHEAR(7)',2X,'SHEAR(8)',2X,'SHEAR(9)',1X
    2,'SHEAR(10)',1X,'SUR. ACCE',/)
     END
```

```
      SUBROUTINE SPLINE (NN,X,Y,FDP,A,B,C,R)
C     ====================================
      IMPLICIT REAL*8(A-H,O-Z)
C
      COMMON RA(18000)
      DIMENSION X(NN), Y(NN), A(NN), B(NN), C(NN), R(NN), FDP(NN)
C
C     THIS IS A PART OF SPLINE INTERPOLATION USED TO CALCULATE
C     THE VALUE OF K2
C
C     THE SPLINE HAS PARABOLIC RUNOUTS
C
      ALAMDA=1.0
      NM2=NN-2
      NM1=NN-1
C
      C(1)=X(2)-X(1)
C
      DO 10 I=2,NM1
      C(I)=X(I+1)-X(I)
      A(I)=C(I-1)
      B(I)=2.*(A(I)+C(I))
      R(I)=6.*((Y(I+1)-Y(I))/C(I)-(Y(I)-Y(I-1))/C(I-1))
   10 CONTINUE
C
      B(2)=B(2)+ALAMDA*C(1)
      B(NM1)=B(NM1)+ALAMDA*C(NM1)
C
      DO 20 I=3,NM1
      T=A(I)/B(I-1)
      B(I)=B(I)-T*C(I-1)
      R(I)=R(I)-T*R(I-1)
   20 CONTINUE
C
      FDP(NM1)=R(NM1)/B(NM1)
C
      DO 30 I=2,NM2
      NMI=NN-I
      FDP(NMI)=(R(NMI)-C(NMI)*FDP(NMI+1))/B(NMI)
   30 CONTINUE
C
      FDP(1)=ALAMDA*FDP(2)
      FDP(NN)=ALAMDA*FDP(NM1)
C
      RETURN
      END
```

```
      SUBROUTINE TLOAD (NTP,FF,NT,ND,SM,ICOUNT,ACC)
C     =================================
      IMPLICIT REAL*8(A-H,O-Z)
C
      COMMON RA(18000)
      COMMON /THREE/ DELT,TMAX,AA,ANOMEG
      DIMENSION FF(ND,NTP), SM(ND,ND), ACC(NT)
C
C     SUBROUTINE CALCULATES LOAD HISTORY
C
      IF(ICOUNT.NE.1) GO TO 40
C
      NT1=NT+1
      PI=4.*DATAN(1.D0)
      OMEGA=ANOMEG*PI
C
C     CALCULATE LOAD AT EACH STEP OF DELT = 0.01 SEC
C
      J=1
      DO 10 I=1,ND
   10 FF(I,J)=0.0
C
      DO 30 I=1,ND
      DO 20 J=1,NT
      AJ=J
      T=AJ*DELT
C
      FF(I,J+1)=-SM(I,I)*AA*DSIN(OMEGA*T)
   20 CONTINUE
   30 CONTINUE
C
      GO TO 80
   40 CONTINUE
C
      READ (5,90) (ACC(I),I=1,NT)
C
C     CALCULATE LOAD AT EACH STEP OF DELT = 0.01 SEC
C
      J=1
      DO 50 I=1,ND
   50 FF(I,J)=0.0
C
      DO 70 I=1,ND
      DO 60 J=1,NT
      FF(I,J+1)=-SM(I,I)*ACC(J)
   60 CONTINUE
   70 CONTINUE
C
   80 CONTINUE
C
      RETURN
C
```

```
90    FORMAT (8F10.0)
      END
```

```
      SUBROUTINE STIFF (EKI,ND,SK)
C     ==================================
      IMPLICIT REAL*8(A-H,O-Z)
      DIMENSION EKI(ND), SK(ND,ND)
C
      DO 10 I=1,ND
      DO 10 J=1,ND
 10   SK(I,J)=0.0
C
      SK(1,1)=EKI(1)
C
      DO 20 I=2,ND
      SK(I,I)=EKI(I-1)+EKI(I)
 20   CONTINUE
C
      DO 30 J=2,ND
      I=J-1
      SK(I,J)=-EKI(I)
 30   CONTINUE
C
      NDM1=ND-1
      DO 40 J=1,NDM1
      I=J+1
      SK(I,J)=-EKI(J)
 40   CONTINUE
C
      RETURN
      END
```

```
      SUBROUTINE DAMP (WN,ZETA,ND,SK,SC)
C     ======================================
      IMPLICIT REAL*8(A-H,O-Z)
      DIMENSION SK(ND,ND), SC(ND,ND)
C
C     CALCULATE CONSTANT A1 IN RAYLEIGH DAMPING
C
      A1=2.*ZETA/WN
C
      DO 10 I=1,ND
      DO 10 J=1,ND
      SC(I,J)=A1*SK(I,J)
 10   CONTINUE
C
      RETURN
      END
```

```
C
      SUBROUTINE DYNA(BIG,SM,SK,SC,FF,GI,H,
C     ==================================================================
     *                    UDI,UVI,UAI,UD,UV,UA,SHEAR,F,SST,A,B,X)
C                         ==========================================
C
      IMPLICIT REAL*8(A-H,O-Z)
C
      COMMON RA(18000)
      COMMON /ONE/ KKK
      COMMON /TWO/ ILIQ
      COMMON /AAA/ ND,LAYDRY,NN,N,NM
      COMMON /BBB/ NT,NDIV,NTP,NDIVP
      COMMON /FOUR/ TSTEP,DELTA,ALPHA,TFIN
C
      DIMENSION SM(ND,ND), SK(ND,ND), SC(ND,ND), A(ND,ND), B(ND), X(ND),
     1 UDI(ND), UVI(ND), UAI(ND), UD(ND), UV(ND), UA(ND), SST(ND), GI(ND
     2), BIG(ND)
      DIMENSION H(ND), SHEAR(ND), F(ND,NDIVP), FF(ND,NTP)
C
C     THIS SUBROUTINE SOLVES THE DYNAMIC EQUATION OF MOTION TO GET
C     THE SHEAR STRAINS
C
      NT1=NDIV+1
C
C     CORELATE THE LOADS WITH TOTAL LOAD GIVEN BY FF
C
      DO 10 I=1,ND
      DO 10 J=1,NT1
   10 F(I,J)=0.0
      DO 30 I=1,ND
      IF(I.LE.ILIQ) GO TO 30
      DO 20 J=1,NT1
      L=J+50*(KKK-1)
      F(I,J)=FF(I,L)
   20 CONTINUE
   30 CONTINUE
C
C     ONLY FOR THE FIRST CYCLE GO THROUGH THE PROCEDURE
C     OF EVALUATING THE INITIAL ACCELERATION AND VARIOUS
C     CONSTANTS IN NEWMARK'S SCHEME FOR STEP-BY-STEP
C     INTEGRATION.
C
      IF(KKK.NE.1) GO TO 80
C
      DO 40 I=1,ND
      DO 40 J=1,ND
   40 A(I,J)=SM(I,J)
C
C
      DO 50 I=1,ND
   50 B(I)=F(I,1)
```

```
C
      DO 60 I=1,ND
      DO 60 J=1,ND
 60   B(I)=B(I)-SC(I,J)*UVI(J)-SK(I,J)*UDI(J)
C
      CALL TRI (A,ND)
      CALL REDUCE (A,X,B,ND)
C
C
      DT=TSTEP
      A0=1./(ALPHA*DT*DT)
      A1=DELTA/(ALPHA*DT)
      A2=1./(ALPHA*DT)
      A3=1./(2.*ALPHA)-1.
      A4=DELTA/ALPHA-1.
      A5=DT*0.5*(DELTA/ALPHA-2.)
      A6=DT*(1.-DELTA)
      A7=DELTA*DT
C
      DO 70 I=1,ND
 70   UAI(I)=X(I)
C
 80   CONTINUE
C
      DO 150 L=1,NDIV
      DO 90 I=1,ND
      DO 90 J=1,ND
 90   A(I,J)=SK(I,J)+A0*SM(I,J)+A1*SC(I,J)
      DO 110 I=1,ND
      B(I)=F(I,L+1)
      DO 100 J=1,ND
 100  B(I)=B(I)+SM(I,J)*(A0*UDI(J)+A2*UVI(J)+A3*UAI(J))+SC(I,J)*(A1*UDI(
     1J)+A4*UVI(J)+A5*UAI(J))
 110  CONTINUE
C
      CALL TRI (A,ND)
      CALL REDUCE (A,X,B,ND)
C
      AL=L
      T=DT*AL
      DO 120 I=1,ND
      UD(I)=X(I)
C
      UA(I)=A0*(UD(I)-UDI(I))-A2*UVI(I)-A3*UAI(I)
C
      UV(I)=UVI(I)+A6*UAI(I)+A7*UA(I)
C
 120  CONTINUE
C     CALCULATE SHEAR STRAINS FOR EACH LAYER
C
      ND1=ND-1
      DO 130 I=1,ND1
```

```
      SST(I)=(UD(I)-UD(I+1))/H(I)
      SHEAR(I)=GI(I)*SST(I)
      SST(I)=DABS(SST(I))
 130  CONTINUE
C
      SST(ND)=UD(ND)/H(ND)
      SHEAR(ND)=GI(ND)*SST(ND)
      SST(ND)=DABS(SST(ND))
C
C     CALCULATE THE MAXIMUM SHEAR STRAIN FOR A PAERIOD
C     OF DT = 0.5 SEC
C
      CALL AMAX (ND,L,SST,BIG)
C     ===================================
C
      DO 140 I=1,ND
      UDI(I)=UD(I)
      UAI(I)=UA(I)
      UVI(I)=UV(I)
 140  CONTINUE
C
      IC=L+50*(KKK-1)
      AIC=IC
      TE=DT*AIC
      WRITE (6,160) TE,(SHEAR(IJ),IJ=2,10),UAI(1)
C
 150  CONTINUE
C
      RETURN
C
 160  FORMAT (F10.5,9F10.3,F10.5)
      END
```

```
      SUBROUTINE AMAX (ND,L,SST,BIG)
C     ============================
      IMPLICIT REAL*8(A-H,O-Z)
C
      DIMENSION SST(ND), BIG(ND)
      IF(L.NE.1) GO TO 20
C
      DO 10 I=1,ND
      BIG(I)=0.0
 10   CONTINUE
C
 20   CONTINUE
C
      DO 30 I=1,ND
      IF(SST(I).GT.BIG(I)) BIG(I)=SST(I)
 30   CONTINUE
C
      RETURN
      END
```

```
      SUBROUTINE SPEVAL (NN,X,Y,FDP,XX,F)
C     ========================================
      IMPLICIT REAL*8(A-H,O-Z)
C
C     THIS SUBROUTINE EVALUATES THE CUBIC SPLINE INTERPOLATED
C     VALUE OF K2
C
C     F=INTERPOLATED VALUE
      DIMENSION X(NN), Y(NN), FDP(NN)
C
C     FIND THE PROPER INTERVAL
C
      NM1=NN-1
      DO 10 I=1,NM1
      IF(XX.LE.X(I+1)) GO TO 20
 10   CONTINUE
      RETURN
C
C     EVALUATE THE CUBIC
C
 20   DXM=XX-X(I)
      DXP=X(I+1)-XX
      DEL=X(I+1)-X(I)
C
      F=FDP(I)*DXP*(DXP*DXP/DEL-DEL)/6.+FDP(I+1)*DXM*(DXM*DXM/DEL-DEL)/6
     1.+Y(I)*DXP/DEL+Y(I+1)*DXM/DEL
      RETURN
      END
```

```
      SUBROUTINE SOURCE (ND,KKK,CHVD,EPSVD,BIG,DELVD)
C     =================================================================
      IMPLICIT REAL*8(A-H,O-Z)
C
      COMMON RA(18000)
      COMMON /FIVE/ C1,C2,C3,C4
C
      DIMENSION CHVD(ND), EPSVD(ND), DELVD(ND), BIG(ND)
C
C     THIS SUBROUTINE CALCULATES VALUE OF THE SOURCE TERM IN THE
C     DIFFUSION EQUATION
C
      DO 10 I=1,ND
      DELVD(I)=C1*(BIG(I)-C2*EPSVD(I))+C3*(EPSVD(I)**2)/(BIG(I)+C4*EPSVD
     1(I))
      CHVD(I)=DELVD(I)
 10   CONTINUE
C
      DO 20 I=1,ND
 20   EPSVD(I)=DELVD(I)+EPSVD(I)
C
C
      RETURN
      END
```

```
      SUBROUTINE DIFF (IFLAG,N,FR,Q,BETA,NM,A,B,C,R,T,BB)
C     ==============================================
C
      IMPLICIT REAL*8(A-H,O-Z)
C
      DIMENSION FR(N), T(N), Q(N), BETA(N), A(N), B(N), C(N), R(N), BB(N
     1)
C
      NM1=N-1
      IF(IFLAG.NE.1) GO TO 30
C
C     TEMPORARY ARRAY IS DENOTED BY T(I)
C     THIS IS EXPLICIT METHOD SCHEME
C     ------------------------------------
C
      DO 10 I=3,NM1
      T(I)=FR(I)+BETA(I)*(FR(I-1)-2.*FR(I)+FR(I+1))+Q(I)
 10   CONTINUE
C
      T(2)=FR(2)+BETA(2)*(-2.*FR(2)+2.*FR(3))+Q(2)
      T(N)=FR(N)+BETA(N)*(-2.*FR(N)+FR(NM1))+Q(N)
C
      DO 20 I=2,N
      FR(I)=T(I)
 20   CONTINUE
      RETURN
C
 30   CONTINUE
C
C     THIS IS CRANK-NICOLSON IMPLICIT SCHEME
C     ------------------------------------------
C
      DO 40 I=2,N
      A(I)=-BETA(I)
      B(I)=2.*(1.+BETA(I))
      C(I)=-BETA(I)
 40   CONTINUE
C     START THE MAIN LOOP
C
      DO 50 I=3,NM1
      R(I)=BETA(I)*(FR(I-1)+FR(I+1))+2.*(1.-BETA(I))*FR(I)+Q(I)
 50   CONTINUE
C
      R(2)=BETA(2)*FR(3)*2.+2.*(1.-BETA(2))*FR(2)+Q(2)
      R(N)=BETA(N)*FR(N-1)+2.*(1.-BETA(N))*FR(N)+Q(N)
C
      CALL SOLVE (N,A,B,C,FR,R,BB)
      RETURN
      END
```

```
      SUBROUTINE STRESS (ND,N,CHVD,DT,ESTI,FR,SIGMAO,SIGMAV,SIGZER,AKO,B
     1B)
C     ==================================================================
C
      IMPLICIT REAL*8(A-H,O-Z)
C
      COMMON RA(18000)
      COMMON /ONE/ KKK
      COMMON /TWO/ ILIQ
C
      DIMENSION BB(ND), SIGMAV(ND), SIGMAO(ND), ESTI(ND), CHVD(ND), SIGZ
     1ER(ND), FR(N)
C
C
C     DEFINE INCREASE IN THE PORE PRESSURE AT THE CENTER OF
C     EACH LAYER
C
      TT=KKK*DT
C
C     BB=INCREASE IN THE PORE PRESSURE
C
      BB(1)=0.0
      J=N
      DO 10 I=2,ND
      BB(I)=FR(J)
      J=J-2
 10   CONTINUE
C
C
      DO 20 I=1,ND
      SIGMAV(I)=SIGZER(I)-BB(I)
      IF(SIGMAV(I).LE.0.0) ILIQ=I
 20   CONTINUE
C
C
      DO 50 I=1,ND
      CHECK=1.E-5*SIGZER(I)
      IF(SIGMAV(I)-CHECK) 30,40,40
 30   SIGMAV(I)=CHECK
 40   CONTINUE
 50   CONTINUE
C
      WRITE (6,80)
C
      WRITE (6,90) TT,(SIGMAV(I),BB(I),I=1,ND)
C
      DO 60 I=1,ND
      SIGMAO(I)=(SIGMAV(I)+2.*AKO*SIGMAV(I))/3.
 60   CONTINUE
C
C     CONVERT SIGMAV INTO ESTI FOR THE NEXT CYCLE
C
```

```
      DO 70 I=1,ND
      ESTI(I)=SIGMAV(I)
 70   CONTINUE
C
C
      RETURN
C
 80   FORMAT (///25X,'NEW EFFECTIVE STRESSES AND PORE PRESSURES ARE',/)
 90   FORMAT (//30X,'TIME=',F10.4//1(25X,F10.4,5X,F10.4))
      END
```

```
      SUBROUTINE TRI (A,ND)
C     ========================
      IMPLICIT REAL*8(A-H,O-Z)
C
      DIMENSION A(ND,ND)
      ND1=ND-1
      TINY=1.E-15
C
      DO 30 I=1,ND1
C
      IF(DABS(A(I,I)).LT.TINY) GO TO 40
C
      J1=I+1
C
      DO 20 J=J1,ND
      IF(A(J,I).EQ.0.) GO TO 20
      FAC=A(J,I)/A(I,I)
      DO 10 K=J1,ND
 10   A(J,K)=A(J,K)-A(I,K)*FAC
 20   CONTINUE
 30   CONTINUE
      RETURN
 40   WRITE (6,50) I,A(I,I)
      STOP
C
 50   FORMAT (//5X,'SMALL PIVOT',I5,F10.4,/)
      END
```

```
      SUBROUTINE REDUCE (A,X,B,ND)
C     =================================
      IMPLICIT REAL*8(A-H,O-Z)
C
      DIMENSION A(ND,ND), B(ND), X(ND)
C
      ND1=ND-1
C
      DO 20 I=1,ND1
      J1=I+1
C
      DO 10 J=J1,ND
   10 B(J)=B(J)-B(I)*A(J,I)/A(I,I)
   20 CONTINUE
C
      X(ND)=B(ND)/A(ND,ND)
C
      DO 40 I=1,ND1
      IB=ND-I
      J1=IB+1
      DO 30 J=J1,ND
   30 B(IB)=B(IB)-A(IB,J)*X(J)
      X(IB)=B(IB)/A(IB,IB)
   40 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE SOLVE (N,A,B,C,X,Q,BB)
C     ================================
      IMPLICIT REAL*8(A-H,O-Z)
C
      DIMENSION A(N), B(N), C(N), X(N), Q(N), BB(N)
C
C     THIS SUBROUTINE SOLVES TRIDIAGONAL SYSTEM UDSING
C     GAUSS ELIMINATION.
C
C     (N-1) IS THE TOTAL NUMBER OF EQUATIONS TO BE SOLVED.
C     BB IS DUMMY ARRAY.
C
C     FORWARD ELIMINATION.
C
      DO 10 I=2,N
      BB(I)=B(I)
 10   CONTINUE
C
      DO 20 I=3,N
      T=A(I)/BB(I-1)
      BB(I)=BB(I)-C(I-1)*T
      Q(I)=Q(I)-Q(I-1)*T
 20   CONTINUE
C
C     BACK SUSTITUTE
C
      X(N)=Q(N)/BB(N)
C
      NM2=N-2
      DO 30 I=1,NM2
      J=N-I
      X(J)=(Q(J)-C(J)*X(J+1))/BB(J)
 30   CONTINUE
C
      RETURN
      END
```

Appendix E

SAMPLE OUTPUT

The sample output for EXAMPLE-1 using explicit method is given below.

```
 THIS  IS THE  DYNAMIC  RESPONSE  ANALYSIS OF  LAYERED  SAND
STRATUM.

    TOTAL NUMBER OF LAYERS                         =    10
 THIS  IS THE  DYNAMIC  RESPONSE  ANALYSIS OF  LAYERED  SAND
STRATUM.

    TOTAL NUMBER OF LAYERS                         =    10
    NUMBER OF DRY LAYERS                           =     1
    NUMBER OF DATA POINTS FOR INTERPOLATION        =    10
    NUMBER OF DIVISIONS OF EACH LAYER              =     2
    TOTAL NUMBER OF SPATIAL DIVISIONS              =    18
    NUMBER OF DIVISIONS OF EXCITATION PERIOD       =  1000
    NUMBER OF DIVISIONS OF EACH CYCLE PERIOD       =    50
```

TOTAL STORAGE USED FOR THIS PROBLEM = 12511

THIS IS INPUT DATA FOR THIS PROBLEM.

```
  50.0000    32.2000    0.0200   122.0000   62.4000   2.6500
40.000 0.4500
   0.0001  0.001   0.010  0.100  0.200  0.400   0.500  0.700
0.800  1.00

   0.4300    0.6200    0.0025
   0.0000
   0.0003   45.0000    0.5000   10.0000
   4.0000    0.0100    0.8050
   0.0100    0.5000    0.2500    0.5000
   0.0000    0.0000
   0.0000    0.0000
   0.0000    0.0000
   0.0000    0.0000
   0.0000    0.0000
   0.0000    0.0000
   0.0000    0.0000
   0.0000    0.0000
   0.0000    0.0000
   0.0000    0.0000
   0.8000    0.7900    0.4500    0.6300
        1
        1
```

SOIL PROPERTIES ARE

TOTAL DEPTH OF SAND STRATA	=	50.0000 ft.
ACCELERATION DUE TO GRAVITY	=	32.2000 ft/sec^2
DAMPING COEFFICIENT	=	0.0200
UNIT WEIGHT OF SATURATED SAND	=	122.0000 lb/ft^3
UNIT WEIGHT OF WATER	=	62.4000 lb/ft^3
SPECIFIC GRAVITY OF SAND	=	2.6500
ANGLE OF FRICTION	=	40.0000 deg.
COEFFICIENT OF EARTH PRESSURE	=	0.3572
VOID RATIO	=	0.7275
UNIT WEIGHT OF DRY SAND	=	95.7212 lb/ft^3
HEIGHT OF EACH LAYER	=	5.0000 ft.
RELATIVE DENSITY OF SAND	=	0.4500

AT TIME T=0.0 SEC

TOTAL STRESS	EFFECTIVE STRESS	PORE PRESSURE
239.3030	239.3030	0.0000
783.6061	627.6061	156.0000
1393.6061	925.6061	468.0000
2003.6061	1223.6061	780.0000
2613.6061	1521.6061	1092.0000
3223.6061	1819.6061	1404.0000
3833.6061	2117.6061	1716.0000
4443.6061	2415.6061	2028.0000
5053.6061	2713.6061	2340.0000
5663.6061	3011.6061	2652.0000

CYCLE NUMBER IS 1

DAMPING RATIO = 0.02000
LAYER FIRST TO LIQUEFY = 0

TIME	SHEAR(2)	SHEAR(3)	SHEAR(4)	SHEAR(5)	SHEAR(6)
0.01000	-0.000	-0.000	-0.000	-0.001	-0.004
0.02000	-0.000	-0.001	-0.004	-0.015	-0.051
0.03000	-0.002	-0.009	-0.033	-0.107	-0.315
0.04000	-0.014	-0.055	-0.175	-0.492	-1.241
0.05000	-0.069	-0.237	-0.665	-1.630	-3.547
0.06000	-0.260	-0.793	-1.955	-4.189	-7.934
0.07000	-0.787	-2.137	-4.653	-8.781	-14.694
0.08000	-1.969	-4.791	-9.287	-15.639	-23.626
0.09000	-4.172	-9.175	-16.030	-24.554	-34.345
0.10000	-7.625	-15.355	-24.627	-35.106	-46.546
0.11000	-12.229	-22.962	-34.569	-46.907	-59.972
0.12000	-17.511	-31.335	-45.306	-59.580	-74.245
0.13000	-22.802	-39.770	-56.288	-72.620	-88.840
0.14000	-27.527	-47.669	-66.901	-85.362	-103.153
0.15000	-31.403	-54.570	-76.481	-97.090	-116.514
0.16000	-34.407	-60.151	-84.461	-107.139	-128.196
0.17000	-36.631	-64.269	-90.492	-114.964	-137.499
0.18000	-38.144	-66.944	-94.440	-120.189	-143.849
0.19000	-38.947	-68.253	-96.300	-122.634	-146.855
0.20000	-38.989	-68.209	-96.089	-122.248	-146.288
0.21000	-38.196	-66.725	-93.769	-118.991	-142.030
0.22000	-36.499	-63.664	-89.207	-112.761	-133.999
0.23000	-33.849	-58.894	-82.218	-103.389	-122.106
0.24000	-30.199	-52.315	-72.637	-90.727	-106.298
0.25000	-25.498	-43.861	-60.400	-74.741	-86.654
0.26000	-19.698	-33.524	-45.581	-55.605	-63.474
0.27000	-12.811	-21.398	-28.416	-33.721	-37.310
0.28000	-4.956	-7.735	-9.329	-9.697	-8.908
0.29000	3.613	7.031	11.070	15.709	20.876
0.30000	12.531	22.302	32.027	41.658	51.160
0.31000	21.370	37.401	52.727	67.282	81.073
0.32000	29.698	51.674	72.390	91.750	109.762
0.33000	37.156	64.580	90.347	114.299	136.387
0.34000	43.510	75.736	106.072	134.257	160.139
0.35000	48.664	84.917	119.179	151.056	180.274
0.36000	52.618	92.021	129.401	164.245	196.168
0.37000	55.403	97.006	136.565	173.496	207.342
0.38000	57.024	99.840	140.565	178.609	213.488
0.39000	57.439	100.468	141.335	179.484	214.449
0.40000	56.577	98.821	138.833	176.101	210.202
0.41000	54.372	94.839	133.037	168.494	200.842
0.42000	50.795	88.501	123.970	156.763	186.575
0.43000	45.874	79.863	111.741	141.113	167.737

0.44000	39.704	69.082	96.589	121.893	144.809
0.45000	32.438	56.431	78.908	99.617	118.426
0.46000	24.292	42.297	59.239	74.957	89.362
0.47000	15.540	27.162	38.242	48.704	58.495
0.48000	6.506	11.569	16.639	21.709	26.753
0.49000	-2.467	-3.921	-4.843	-5.182	-4.939
0.50000	-11.048	-18.780	-25.526	-31.176	-35.706

SHEAR(7)	SHEAR(8)	SHEAR(9)	SHEAR(10)	SUR. ACCE
0.015	-0.054	-0.186	-0.621	-0.10089
0.162	-0.478	-1.301	-3.202	-0.20019
0.842	-2.043	-4.439	-8.424	-0.29629
2.810	-5.683	-10.170	-16.072	-0.38742
6.872	-11.855	-18.309	-25.889	-0.47111
3.393	-20.372	-28.509	-37.712	-0.54276
2.179	-30.864	-40.589	-51.305	-0.59340
2.852	-43.110	-54.344	-66.373	-0.60794
5.155	-56.915	-69.463	-82.616	-0.56708
8.879	-71.970	-85.619	-99.709	-0.45545
3.702	-87.915	-102.487	-117.295	-0.27357
9.212	-104.387	-119.691	-134.992	-0.04477
4.953	-120.965	-136.804	-152.389	0.19206
0.395	-137.133	-153.351	-169.017	0.40246
4.887	-152.287	-168.769	-184.331	0.57413
7.694	-165.729	-182.380	-197.678	0.71713
8.053	-176.667	-193.394	-208.279	0.84705
5.239	-184.272	-200.935	-215.241	0.96818
8.639	-187.766	-204.113	-217.628	1.07188
7.815	-186.509	-202.139	-214.584	1.14754
2.510	-180.079	-194.460	-205.492	1.19142
2.616	-168.316	-180.862	-190.113	1.20482
8.139	-151.312	-161.501	-168.648	1.18694
9.198	-129.380	-136.857	-141.684	1.13221
6.063	-103.016	-107.633	-110.055	1.03369
9.192	-72.858	-74.629	-74.666	0.88732
9.253	-39.662	-38.664	-36.387	0.69320
7.063	-4.254	-0.554	3.972	0.45546
6.489	32.497	38.875	45.602	0.18298
0.513	69.710	78.752	87.627	-0.10974
4.133	106.487	118.140	129.074	-0.40396
6.467	141.894	156.044	168.896	-0.68070
6.605	174.954	191.428	206.014	-0.92528
3.625	204.667	223.244	239.352	-1.13000
6.646	230.061	250.470	267.862	-1.29394
4.896	250.257	272.154	290.552	-1.42030
7.764	264.525	287.477	306.550	-1.51261
4.822	272.328	295.814	315.180	-1.57172
5.841	273.359	296.795	316.039	-1.59488
0.782	267.562	290.352	309.054	-1.57727
9.793	255.133	276.719	294.481	-1.51462
3.199	236.500	256.402	272.874	-1.40520

1.480	212.281	230.123	245.014	-1.25033
5.259	183.230	198.742	211.827	-1.05382
5.286	150.200	163.194	174.300	-0.82137
2.415	114.106	124.441	133.430	-0.56070
7.572	75.902	83.456	90.209	-0.28205
1.725	36.568	41.221	45.631	0.00196
4.159	-2.907	-1.259	0.719	0.27751
9.142	-41.536	-42.956	-43.465	0.53162

TIME= 0.5000 SEC

INITIAL EFFECTIVE STRESS	NEW PORE PRESSURE
239.3030	0.0000
627.6061	60.5874
925.6061	101.1477
1223.6061	137.6045
1521.6061	170.2354
1819.6061	199.0791
2117.6061	224.1054
2415.6061	245.2844
2713.6061	262.6217
3011.6061	276.1750

CYCLE NUMBER IS 2

DAMPING RATIO = 0.02000
LAYER FIRST TO LIQUEFY = 0

TIME	SHEAR(2)	SHEAR(3)	SHEAR(4)	SHEAR(5)	SHEAR(6)
0.51000	-12.885	-21.457	-29.131	-35.794	-41.451
0.52000	-17.699	-29.855	-40.833	-50.575	-59.057
0.53000	-21.782	-37.396	-51.537	-64.234	-75.456
0.54000	-25.141	-43.918	-61.080	-76.593	-90.456
0.55000	-28.014	-49.388	-69.330	-87.516	-103.937
0.56000	-30.626	-53.958	-76.260	-96.934	-115.848
0.57000	-32.992	-57.861	-82.010	-104.889	-126.177
0.58000	-34.973	-61.248	-86.839	-111.538	-134.912
0.59000	-36.489	-64.133	-90.976	-117.076	-142.049
0.60000	-37.625	-66.470	-94.480	-121.615	-147.605
0.61000	-38.534	-68.260	-97.246	-125.103	-151.598
0.62000	-39.293	-69.546	-99.108	-127.364	-154.002
0.63000	-39.849	-70.317	-99.953	-128.217	-154.717
0.64000	-40.075	-70.458	-99.721	-127.561	-153.612
0.65000	-39.837	-69.789	-98.352	-125.371	-150.610
0.66000	-39.030	-68.155	-95.748	-121.639	-145.721
0.67000	-37.580	-65.474	-91.807	-116.339	-139.020
0.68000	-35.454	-61.732	-86.481	-109.456	-130.596
0.69000	-32.678	-56.960	-79.811	-101.029	-120.530
0.70000	-29.333	-51.244	-71.915	-91.171	-108.910
0.71000	-25.535	-44.729	-62.968	-80.055	-95.848
0.72000	-21.408	-37.610	-53.174	-67.863	-81.466
0.73000	-17.066	-30.090	-42.741	-54.771	-65.899
0.74000	-12.607	-22.330	-31.850	-40.935	-49.294
0.75000	-8.106	-14.433	-20.632	-26.507	-31.827
0.76000	-3.605	-6.444	-9.168	-11.632	-13.706
0.77000	0.897	1.628	2.488	3.550	4.850
0.78000	5.432	9.791	14.287	18.912	23.638
0.79000	10.038	18.043	26.169	34.336	42.475
0.80000	14.729	26.365	38.065	49.708	61.182
0.81000	19.484	34.710	49.892	64.896	79.559
0.82000	24.241	42.995	61.544	79.741	97.371
0.83000	28.911	51.100	72.869	94.036	114.352
0.84000	33.395	58.871	83.661	107.528	130.215
0.85000	37.586	66.120	93.666	119.933	144.666
0.86000	41.375	72.642	102.613	130.951	157.410
0.87000	44.647	78.231	110.236	140.295	168.165
0.88000	47.287	82.704	116.306	147.711	176.671
0.89000	49.188	85.908	120.639	152.993	182.712
0.90000	50.274	87.737	123.108	155.991	186.114
0.91000	50.503	88.131	123.637	156.608	186.756
0.92000	49.876	87.080	122.199	154.798	184.559

0.93000	48.428	84.616	118.814	150.556	179.487
0.94000	46.214	80.808	113.538	143.912	171.544
0.95000	43.298	75.741	106.451	134.932	160.772
0.96000	39.736	69.500	97.652	123.708	147.258
0.97000	35.575	62.166	87.244	110.362	131.132
0.98000	30.846	53.804	75.333	95.034	112.574
0.99000	25.576	44.473	62.024	77.891	91.808
1.00000	19.789	34.234	47.435	59.120	69.100

SHEAR(7)	SHEAR(8)	SHEAR(9)	SHEAR(10)	SUR. ACCE
-46.136	-49.892	-52.768	-54.841	0.55577
-66.294	-72.327	-77.243	-81.233	0.59777
-85.205	-93.550	-100.655	-106.761	0.61442
102.696	-113.435	-122.861	-131.092	0.65476
118.675	-131.867	-143.603	-153.813	0.71383
133.071	-148.657	-162.524	-174.535	0.75987
145.765	-163.528	-179.279	-192.911	0.77777
156.573	-176.196	-193.578	-208.624	0.77939
165.319	-186.439	-205.178	-221.394	0.78287
171.929	-194.128	-213.889	-231.001	0.79422
176.430	-199.221	-219.598	-237.301	0.80925
178.881	-201.756	-222.304	-240.253	0.82491
179.294	-201.819	-222.107	-239.948	0.84298
177.620	-199.491	-219.179	-236.595	0.86401
173.800	-194.828	-213.706	-230.467	0.88189
167.840	-187.883	-205.848	-221.806	0.88641
159.842	-178.753	-195.723	-210.761	0.87013
149.961	-167.582	-183.416	-197.380	0.83229
138.341	-154.512	-168.999	-181.676	0.77709
125.073	-139.633	-152.540	-163.693	0.70950
110.199	-122.977	-134.105	-143.541	0.63296
-93.767	-104.571	-113.774	-121.371	0.54988
-75.873	-84.495	-91.655	-97.332	0.46294
-56.675	-62.914	-67.902	-71.575	0.37529
-36.390	-40.057	-42.719	-44.287	0.28939
-15.265	-16.190	-16.373	-15.736	0.20557
6.438	8.398	10.811	13.709	0.12150
28.456	33.385	38.439	43.594	0.03298
50.523	58.414	66.071	73.416	-0.06430
72.364	83.103	93.243	102.661	-0.17299
93.687	107.067	119.499	130.825	-0.29310
114.185	129.939	144.416	157.446	-0.42223
133.547	151.372	167.618	182.116	-0.55668
151.465	171.048	188.772	204.488	-0.69270
167.644	188.673	207.591	224.274	-0.82690
181.805	203.983	223.822	241.222	-0.95590
193.683	216.735	237.235	255.109	-1.07562
203.033	226.703	247.617	265.719	-1.18115
209.636	233.670	254.755	272.844	-1.26747
213.301	237.435	258.444	276.279	-1.33067
213.874	237.817	258.488	275.826	-1.36888

211.242	234.670	254.718	271.308	-1.38236
205.335	227.892	247.008	262.592	-1.37279
196.127	217.432	235.292	249.610	-1.34222
183.645	203.304	219.580	232.382	-1.29243
167.968	185.593	199.971	211.023	-1.22447
149.244	164.466	176.656	185.753	-1.13870
127.684	140.171	149.919	156.888	-1.03484
103.571	113.040	120.135	124.837	-0.91221
77.244	83.475	87.756	90.091	-0.77001

TIME= 1.0000 SEC

INITIAL EFFECTIVE STRESS	NEW PORE PRESSURE
239.3030	0.0000
627.6061	109.8295
925.6061	186.2927
1223.6061	254.9081
1521.6061	316.7066
1819.6061	371.6062
2117.6061	419.4646
2415.6061	460.1724
2713.6061	493.6976
3011.6061	520.5481

CYCLE NUMBER IS 3

DAMPING RATIO = 0.02000
LAYER FIRST TO LIQUEFY = 0

TIME	SHEAR(2)	SHEAR(3)	SHEAR(4)	SHEAR(5)	SHEAR(6)
1.01000	12.665	21.534	29.222	35.688	40.877
1.02000	6.380	10.565	13.899	16.252	17.607
1.03000	-0.262	-0.900	-2.068	-3.908	-6.427
1.04000	-7.114	-12.661	-18.447	-24.530	-30.933
1.05000	-13.958	-24.518	-34.971	-45.326	-55.602
1.06000	-20.626	-36.242	-51.357	-65.976	-80.089
1.07000	-27.051	-47.601	-67.319	-86.141	-104.007
1.08000	-33.209	-58.408	-82.574	-105.461	-126.923
1.09000	-39.033	-68.537	-96.860	-123.572	-148.391
1.10000	-44.411	-77.875	-109.945	-140.119	-167.988
1.11000	-49.227	-86.270	-121.622	-154.799	-185.351
1.12000	-53.395	-93.538	-131.687	-167.371	-200.181
1.13000	-56.846	-99.504	-139.938	-177.636	-212.232
1.14000	-59.502	-104.034	-146.196	-185.412	-221.291
1.15000	-61.277	-107.037	-150.321	-190.517	-227.153
1.16000	-62.105	-108.445	-152.215	-192.788	-229.629
1.17000	-61.962	-108.202	-151.799	-192.102	-228.559
1.18000	-60.854	-106.269	-149.008	-188.377	-223.835
1.19000	-58.796	-102.632	-143.799	-181.571	-215.416
1.20000	-55.794	-97.297	-136.167	-171.687	-203.333
1.21000	-51.850	-90.291	-126.157	-158.787	-187.691
1.22000	-46.976	-81.658	-113.861	-143.005	-168.668
1.23000	-41.198	-71.470	-99.417	-124.548	-146.519
1.24000	-34.569	-59.837	-83.011	-103.676	-121.559
1.25000	-27.176	-46.920	-64.875	-80.695	-94.155
1.26000	-19.136	-32.921	-45.285	-55.945	-64.709
1.27000	-10.598	-18.081	-24.557	-29.801	-33.659
1.28000	-1.729	-2.667	-3.033	-2.672	-1.478
1.29000	7.300	13.045	18.921	24.998	31.318
1.30000	16.325	28.776	40.927	52.742	64.183
1.31000	25.193	44.253	62.600	80.073	96.547
1.32000	33.763	59.216	83.558	106.502	127.832
1.33000	41.897	73.412	103.430	131.552	157.472
1.34000	49.463	86.597	121.864	154.768	184.923
1.35000	56.329	98.538	138.532	175.729	209.676
1.36000	62.367	109.018	153.128	194.048	231.267
1.37000	67.454	117.833	165.379	209.382	249.286
1.38000	71.484	124.804	175.039	221.426	263.374
1.39000	74.367	129.778	181.900	229.926	273.233
1.40000	76.032	132.633	185.795	234.673	278.622
1.41000	76.434	133.283	186.602	235.517	279.368
1.42000	75.544	131.677	184.247	232.368	275.372

1.43000	73.357	127.805	178.713	225.203	266.622
1.44000	69.886	121.688	170.035	214.078	253.192
1.45000	65.163	113.392	158.311	199.122	235.247
1.46000	59.246	103.019	143.695	180.545	213.045
1.47000	52.213	90.716	126.403	158.626	186.923
1.48000	44.172	76.673	106.707	133.714	157.295
1.49000	35.253	61.121	84.931	106.215	124.641
1.50000	25.612	44.328	61.442	76.586	89.499

SHEAR(7)	SHEAR(8)	SHEAR(9)	SHEAR(10)	SUR. ACCE
44.763	47.344	48.621	48.585	-0.58820
17.985	17.414	15.911	13.475	-0.39842
-9.586	-13.340	-17.656	-22.482	-0.20729
-37.622	-44.543	-51.618	-58.707	-0.02326
-65.777	-75.779	-85.467	-94.658	0.16300
-93.662	-106.587	-118.692	-129.835	0.35929
120.832	-136.481	-150.817	-163.752	0.56127
146.809	-164.986	-181.380	-195.927	0.75858
171.118	-191.641	-209.914	-225.876	0.94538
193.315	-215.988	-235.938	-253.110	1.12227
212.996	-237.573	-258.972	-277.134	1.29047
229.791	-255.964	-278.546	-297.451	1.44704
243.377	-270.773	-294.217	-313.586	1.58591
253.479	-281.661	-305.593	-325.117	1.70162
259.868	-288.354	-312.353	-331.701	1.79120
262.344	-290.635	-314.269	-333.101	1.85327
260.741	-288.354	-311.206	-329.196	1.88679
254.949	-281.429	-303.122	-319.975	1.89099
244.933	-269.857	-290.057	-305.516	1.86558
230.753	-253.723	-272.132	-285.970	1.81040
212.558	-233.205	-249.542	-261.553	1.72469
190.572	-208.561	-222.559	-232.551	1.60699
165.090	-180.116	-191.531	-199.327	1.45619
136.463	-148.255	-156.875	-162.333	1.27274
105.099	-113.423	-119.080	-122.097	1.05915
-71.459	-76.128	-78.702	-79.218	0.81959
-36.046	-36.938	-36.355	-34.349	0.55926
0.595	3.536	7.296	11.809	0.28375
37.881	44.648	51.553	58.518	-0.00121
75.200	85.730	95.696	105.014	-0.29017
111.917	126.093	138.990	150.525	-0.57819
147.386	165.041	180.699	194.282	-0.86091
180.968	201.878	220.088	235.526	-1.13420
212.044	235.928	256.443	273.515	-1.39377
240.031	266.551	289.081	307.535	-1.63491
264.396	293.155	317.362	336.920	-1.85270
284.666	315.210	340.713	361.064	-2.04234
300.430	332.258	358.637	379.451	-2.19958
311.348	343.923	370.732	391.664	-2.32090
317.153	349.920	376.704	397.406	-2.40354
317.662	350.062	376.366	396.495	-2.44541

312.779	344.265	369.650	388.876	-2.44505
302.504	332.549	356.597	374.608	-2.40160
286.938	315.041	337.359	353.867	-2.31482
266.281	291.972	312.196	326.935	-2.18518
240.830	263.675	281.467	294.197	-2.01392
210.972	230.574	245.632	256.141	-1.80316
177.176	193.185	205.244	213.352	-1.55603
139.984	152.104	160.941	166.504	-1.27668
100.003	107.995	113.439	116.353	-0.97027

TIME= 1.5000 SEC

INITIAL EFFECTIVE STRESS	NEW PORE PRESSURE
239.3030	0.0000
627.6061	181.6781
925.6061	309.6869
1223.6061	425.7337
1521.6061	530.3441
1819.6061	622.7425
2117.6061	702.2041
2415.6061	768.2149
2713.6061	820.9432
3011.6061	860.6145

CYCLE NUMBER IS 4

DAMPING RATIO = 0.02000
LAYER FIRST TO LIQUEFY = 0

TIME	SHEAR(2)	SHEAR(3)	SHEAR(4)	SHEAR(5)	SHEAR(6)
1.51000	13.830	23.016	30.956	37.666	43.158
1.52000	4.201	7.078	9.365	10.994	11.923
1.53000	-5.493	-9.077	-12.529	-16.047	-19.742
1.54000	-14.854	-25.048	-34.360	-43.112	-51.513
1.55000	-23.639	-40.449	-55.750	-69.852	-83.055
1.56000	-31.760	-54.979	-76.326	-95.901	-113.991
1.57000	-39.243	-68.482	-95.773	-120.869	-143.861
1.58000	-46.156	-80.933	-113.864	-144.353	-172.110
1.59000	-52.558	-92.379	-130.460	-165.956	-198.150
1.60000	-58.468	-102.849	-145.464	-185.334	-221.464
1.61000	-63.859	-112.299	-158.760	-202.233	-241.697
1.62000	-68.655	-120.593	-170.193	-216.496	-258.652
1.63000	-72.739	-127.531	-179.580	-228.029	-272.222
1.64000	-75.967	-132.905	-186.750	-236.744	-282.305
1.65000	-78.192	-136.540	-191.556	-242.507	-288.761
1.66000	-79.298	-138.319	-193.867	-245.142	-291.415
1.67000	-79.225	-138.168	-193.555	-244.459	-290.081
1.68000	-77.974	-136.043	-190.500	-240.292	-284.597
1.69000	-75.583	-131.918	-184.608	-232.525	-274.850
1.70000	-72.091	-125.780	-175.832	-221.112	-260.816
1.71000	-67.518	-117.642	-164.193	-206.091	-242.576
1.72000	-61.863	-107.549	-149.782	-187.599	-220.336
1.73000	-55.125	-95.577	-132.760	-165.880	-194.413
1.74000	-47.330	-81.841	-113.359	-141.274	-165.210
1.75000	-38.555	-66.514	-91.871	-114.185	-133.188
1.76000	-28.937	-49.831	-68.645	-85.048	-98.826
1.77000	-18.670	-32.096	-44.070	-54.311	-62.609
1.78000	-7.984	-13.659	-18.557	-22.420	-25.020
1.79000	2.879	5.115	7.474	10.177	13.448
1.80000	13.692	23.878	33.609	43.020	52.279
1.81000	24.265	42.326	59.454	75.634	90.916
1.82000	34.456	60.208	84.634	107.530	128.773
1.83000	44.165	77.312	108.804	138.219	165.242
1.84000	53.318	93.458	131.636	167.225	199.717
1.85000	61.849	108.473	152.824	194.097	231.621
1.86000	69.678	122.180	172.074	218.419	260.422
1.87000	76.702	134.389	189.103	239.813	285.643
1.88000	82.793	144.896	203.638	257.936	306.871
1.89000	87.812	153.487	215.415	272.480	323.749
1.90000	91.617	159.955	224.188	283.171	335.973
1.91000	94.088	164.112	229.731	289.766	343.287
1.92000	95.130	165.805	231.855	292.059	345.483
1.93000	94.681	164.926	230.417	289.893	342.410

1.94000	92.714	161.418	225.334	283.172	333.983
1.95000	89.230	155.275	216.586	271.876	320.204
1.96000	84.258	146.539	204.228	256.074	301.174
1.97000	77.851	135.301	188.387	235.935	277.102
1.98000	70.084	121.701	169.268	211.720	248.302
1.99000	61.059	105.924	147.143	183.784	215.186
2.00000	50.905	88.207	122.353	152.554	178.248

SHEAR(7)	SHEAR(8)	SHEAR(9)	SHEAR(10)	SUR. ACCE
47.442	50.522	52.362	52.898	-0.58964
12.118	11.536	10.115	7.700	-0.26461
-23.709	-28.043	-32.834	-38.077	0.05406
-59.723	-67.866	-75.947	-83.630	0.34754
-95.567	-107.459	-118.532	-128.368	0.61227
-130.782	-146.205	-159.942	-171.809	0.85469
-164.784	-183.449	-199.650	-213.459	1.08293
-196.923	-218.602	-237.181	-252.782	1.30169
-226.584	-251.152	-272.011	-289.217	1.51196
-253.249	-280.592	-303.566	-322.185	1.71322
-276.503	-306.399	-331.258	-351.089	1.90466
-296.010	-328.069	-354.525	-375.322	2.08454
-311.498	-345.185	-372.849	-394.302	2.24865
-322.767	-357.437	-385.797	-407.530	2.38997
-329.667	-364.613	-393.058	-414.642	2.50032
-332.066	-366.576	-394.473	-415.453	2.57304
-329.827	-363.250	-390.024	-409.973	2.60516
-322.833	-354.625	-379.811	-398.379	2.59762
-311.023	-340.757	-364.024	-380.957	2.55342
-294.436	-321.782	-342.913	-358.040	2.47486
-273.225	-297.923	-316.764	-329.958	2.36163
-247.657	-269.481	-285.887	-297.031	2.21089
-218.087	-236.816	-250.621	-259.587	2.01928
-184.938	-200.332	-211.341	-217.990	1.78535
-148.672	-160.470	-168.474	-172.674	1.51112
-109.779	-117.718	-122.517	-124.159	1.20208
-68.768	-72.614	-74.043	-73.054	0.86613
-26.172	-25.749	-23.698	-20.050	0.51230
17.446	22.235	27.806	34.095	0.14964
61.488	70.653	79.712	88.570	-0.21368
105.318	118.790	131.234	142.538	-0.57114
148.267	165.905	181.572	195.156	-0.91848
189.640	211.244	229.925	245.589	-1.25358
228.740	254.050	275.501	293.020	-1.57559
264.894	293.588	317.530	336.659	-1.88351
297.471	329.160	355.273	375.745	-2.17499
325.907	360.129	388.044	409.563	-2.44580
349.712	385.934	415.222	437.458	-2.69009
368.473	406.098	436.278	458.870	-2.90124
381.848	420.238	450.787	473.350	-3.07286
389.565	428.062	458.443	480.587	-3.19946
391.421	429.377	459.065	480.412	-3.27684

387.288	424.088	452.595	472.796	-3.30218
377.118	412.201	439.089	457.830	-3.27389
360.958	393.819	418.706	435.716	-3.19143
338.956	369.144	391.697	406.743	-3.05510
311.364	338.471	358.398	371.277	-2.86599
278.535	302.186	319.220	329.759	-2.62597
240.921	260.761	274.656	282.701	-2.33785
199.054	214.754	225.279	230.697	-2.00556

TIME= 2.0000 SEC

INITIAL EFFECTIVE STRESS	NEW PORE PRESSURE
239.3030	0.0000
627.6061	265.6453
925.6061	458.5906
1223.6061	637.1662
1521.6061	799.9488
1819.6061	943.8350
2117.6061	1066.0326
2415.6061	1164.5108
2713.6061	1238.7626
3011.6061	1288.9556

CYCLE NUMBER IS 5

DAMPING RATIO = 0.02000
LAYER FIRST TO LIQUEFY = 0

TIME	SHEAR(2)	SHEAR(3)	SHEAR(4)	SHEAR(5)	SHEAR(6)
2.01000	34.390	55.712	73.361	87.997	100.250
2.02000	23.266	38.549	51.236	61.641	70.116
2.03000	11.373	20.413	28.162	34.408	39.134
2.04000	-0.374	1.927	4.519	6.495	7.333
2.05000	-11.168	-16.193	-19.257	-21.910	-25.302
2.06000	-20.621	-33.273	-42.683	-50.596	-58.764
2.07000	-28.836	-48.882	-65.289	-79.297	-92.887
2.08000	-36.203	-62.985	-86.734	-107.644	-127.207
2.09000	-43.109	-75.920	-106.898	-135.157	-160.921
2.10000	-49.793	-88.185	-125.872	-161.285	-193.039
2.11000	-56.373	-100.183	-143.827	-185.519	-222.663
2.12000	-62.927	-112.051	-160.830	-207.510	-249.237
2.13000	-69.490	-123.644	-176.745	-227.129	-272.617
2.14000	-75.978	-134.623	-191.273	-244.424	-292.944
2.15000	-82.133	-144.578	-204.090	-259.492	-310.420
2.16000	-87.568	-153.117	-214.956	-272.354	-325.126
2.17000	-91.894	-159.929	-223.729	-282.889	-336.961
2.18000	-94.850	-164.818	-230.295	-290.851	-345.667
2.19000	-96.368	-167.696	-234.494	-295.920	-350.889
2.20000	-96.552	-168.557	-236.108	-297.753	-352.230
2.21000	-95.593	-167.433	-234.906	-296.014	-349.296
2.22000	-93.660	-164.351	-230.704	-290.406	-341.745
2.23000	-90.834	-159.311	-223.392	-280.707	-329.348
2.24000	-87.072	-152.274	-212.931	-266.819	-312.043
2.25000	-82.237	-143.165	-199.329	-248.800	-289.965
2.26000	-76.156	-131.888	-182.636	-226.865	-263.440
2.27000	-68.689	-118.366	-162.957	-201.353	-232.932
2.28000	-59.782	-102.594	-140.474	-172.675	-198.969
2.29000	-49.498	-84.694	-115.457	-141.267	-162.071
2.30000	-38.018	-64.937	-88.270	-107.558	-122.698
2.31000	-25.615	-43.732	-59.351	-71.960	-81.246
2.32000	-12.624	-21.571	-29.187	-34.876	-38.076
2.33000	0.600	1.040	1.725	3.280	6.437
2.34000	13.734	23.645	32.906	42.063	51.855
2.35000	26.521	45.877	63.920	80.994	97.652
2.36000	38.799	67.467	94.376	119.554	143.210
2.37000	50.494	88.235	123.931	157.210	187.849
2.38000	61.599	108.060	152.269	193.425	230.857
2.39000	72.132	126.846	179.098	227.686	271.537
2.40000	82.090	144.484	204.132	259.517	309.238
2.41000	91.420	160.830	227.091	288.482	343.382
2.42000	100.008	175.685	247.689	314.196	373.479

2.43000	107.682	188.803	265.630	336.313	399.117
2.44000	114.239	199.901	280.612	354.523	419.954
2.45000	119.472	208.693	292.333	368.538	435.696
2.46000	123.198	214.910	300.507	378.087	446.072
2.47000	125.277	218.335	304.877	382.908	450.827
2.48000	125.619	218.807	305.229	382.760	449.719
2.49000	124.184	216.235	301.407	377.439	442.546
2.50000	120.971	210.581	293.314	366.800	429.166

SHEAR(7)	SHEAR(8)	SHEAR(9)	SHEAR(10)	SUR. ACCE
110.598	119.281	126.232	130.910	-1.50824
76.903	82.032	85.164	85.310	-1.00188
42.267	43.523	42.258	37.958	-0.52648
6.554	3.538	-2.213	-9.691	-0.14898
-30.379	-37.856	-47.394	-56.882	0.14975
-68.491	-80.133	-92.360	-103.395	0.41624
-107.372	-122.462	-136.566	-149.146	0.67391
-146.248	-164.060	-179.816	-193.965	0.91960
-184.167	-204.393	-221.973	-237.579	1.14824
-220.258	-243.100	-262.731	-279.651	1.36921
-253.865	-279.779	-301.599	-319.771	1.60072
-284.530	-313.877	-337.980	-357.403	1.85526
-311.916	-344.748	-371.209	-391.860	2.13227
-335.775	-371.799	-400.568	-422.333	2.42080
-355.962	-394.573	-425.332	-447.959	2.70495
-372.420	-412.757	-444.850	-467.921	2.96690
-385.103	-426.138	-458.638	-481.570	3.18880
-393.876	-434.548	-466.421	-488.524	3.35690
-398.468	-437.831	-468.123	-488.725	3.46684
-398.512	-435.835	-463.827	-482.405	3.52545
-393.643	-428.430	-453.723	-469.990	3.54625
-383.591	-415.560	-438.056	-451.955	3.54088
-368.244	-397.280	-417.089	-428.711	3.51220
-347.664	-373.763	-391.066	-400.544	3.45298
-322.074	-345.270	-360.204	-367.623	3.35009
-291.832	-312.112	-324.696	-330.060	3.19064
-257.379	-274.617	-284.738	-287.977	2.96645
-219.198	-233.129	-240.568	-241.572	2.67554
-177.768	-188.025	-192.500	-191.157	2.32160
-133.539	-139.735	-140.960	-137.175	1.91270
-86.935	-88.743	-86.486	-80.205	1.46040
-38.376	-35.585	-29.718	-20.943	0.97871
11.694	19.155	28.633	39.819	0.48254
62.771	74.852	87.812	101.241	-0.01454
114.264	130.831	147.042	162.472	-0.50246
165.497	186.362	205.542	222.687	-0.97609
215.712	240.666	262.527	281.098	-1.43494
264.107	292.926	317.210	336.947	-1.88142
309.877	342.318	368.805	389.481	-2.31827
352.257	388.038	416.521	437.935	-2.74611
390.558	429.334	459.578	481.523	-3.16203

424.187	465.518	497.221	519.456	-3.55934
452.644	495.984	528.742	550.971	-3.92856
475.514	520.208	553.511	575.384	-4.25892
492.445	537.749	571.005	592.129	-4.53996
503.139	548.258	580.831	600.801	-4.76275
507.337	551.477	582.741	601.167	-4.92063
504.830	547.248	576.631	593.173	-5.00930
495.469	535.510	562.537	576.919	-5.02655
479.183	516.306	540.611	552.638	-4.97173

TIME= 2.5000 SEC

INITIAL EFFECTIVE STRESS	NEW PORE PRESSURE
239.3030	0.0000
627.6061	378.4290
925.6061	668.7290
1223.6061	949.3483
1521.6061	1212.9518
1819.6061	1448.7770
2117.6061	1644.7080
2415.6061	1791.8976
2713.6061	1887.0133
3011.6061	1931.4199

CYCLE NUMBER IS 6

DAMPING RATIO = 0.02000
LAYER FIRST TO LIQUEFY = 0

TIME	SHEAR(2)	SHEAR(3)	SHEAR(4)	SHEAR(5)	SHEAR(6)
2.51000	87.577	123.660	140.829	150.300	161.236
2.52000	76.665	113.336	132.704	143.587	154.610
2.53000	60.781	98.666	122.468	136.672	148.755
2.54000	43.384	80.875	109.946	129.030	143.165
2.55000	27.904	61.835	95.253	120.078	137.158
2.56000	16.417	43.790	78.985	109.319	129.877
2.57000	9.183	28.739	62.229	96.476	120.344
2.58000	5.240	17.814	46.339	81.601	107.592
2.59000	3.348	11.010	32.517	65.068	90.890
2.60000	2.592	7.399	21.392	47.467	69.987
2.61000	2.439	5.618	12.784	29.416	45.296
2.62000	2.496	4.342	5.776	11.379	17.900
2.63000	2.327	2.510	-0.968	-6.434	-10.641
2.64000	1.432	-0.657	-8.771	-24.048	-38.655
2.65000	-0.654	-5.729	-18.590	-41.605	-64.753
2.66000	-4.278	-13.107	-30.837	-59.228	-88.129
2.67000	-9.619	-22.970	-45.393	-76.925	-108.660
2.68000	-16.675	-35.198	-61.750	-94.580	-126.801
2.69000	-25.233	-49.336	-79.192	-112.018	-143.331
2.70000	-34.859	-64.630	-96.962	-129.080	-159.075
2.71000	-44.922	-80.146	-114.371	-145.685	-174.689
2.72000	-54.675	-94.932	-130.863	-161.821	-190.561
2.73000	-63.391	-108.169	-146.032	-177.504	-206.814
2.74000	-70.501	-119.284	-159.611	-192.711	-223.367
2.75000	-75.698	-128.007	-171.462	-207.334	-239.997
2.76000	-78.983	-134.369	-181.546	-221.170	-256.378
2.77000	-80.636	-138.657	-189.905	-233.942	-272.086
2.78000	-81.124	-141.329	-196.647	-245.338	-286.601
2.79000	-80.990	-142.918	-201.927	-255.052	-299.322
2.80000	-80.729	-143.931	-205.922	-262.809	-309.610
2.81000	-80.697	-144.769	-208.800	-268.377	-316.862
2.82000	-81.067	-145.658	-210.675	-271.571	-320.594
2.83000	-81.820	-146.625	-211.571	-272.254	-320.517
2.84000	-82.778	-147.499	-211.392	-270.338	-316.572
2.85000	-83.650	-147.941	-209.923	-265.790	-308.930
2.86000	-84.088	-147.505	-206.857	-258.637	-297.956
2.87000	-83.731	-145.704	-201.853	-248.961	-284.135
2.88000	-82.254	-142.089	-194.602	-236.891	-267.992
2.89000	-79.400	-136.311	-184.889	-222.598	-250.012
2.90000	-75.014	-128.178	-172.642	-206.275	-230.582
2.91000	-69.059	-117.685	-157.950	-188.122	-209.958
2.92000	-61.633	-105.019	-141.057	-168.344	-188.260

2.93000	-52.959	-90.533	-122.323	-147.135	-165.497
2.94000	-43.366	-74.709	-102.189	-124.682	-141.614
2.95000	-33.248	-58.096	-81.121	-101.168	-116.535
2.96000	-23.017	-41.241	-59.571	-76.780	-90.218
2.97000	-13.044	-24.634	-37.941	-51.711	-62.691
2.98000	-3.619	-8.659	-16.563	-26.176	-34.081
2.99000	5.082	6.440	4.315	-0.408	-4.613
3.00000	13.006	20.562	24.523	25.335	25.387

SHEAR(7)	SHEAR(8)	SHEAR(9)	SHEAR(10)	SUR. ACCE
178.407	201.927	230.108	259.839	-4.26727
170.561	191.857	216.031	235.155	-3.13912
163.643	182.031	199.555	204.937	-2.14779
157.125	171.370	179.361	172.945	-1.53820
150.167	158.622	155.633	141.880	-1.20646
141.635	142.845	129.842	112.990	-0.99159
130.287	123.794	103.850	86.413	-0.83713
115.072	101.978	79.005	61.769	-0.76275
95.440	78.335	55.733	38.619	-0.77604
71.520	53.758	33.662	16.615	-0.83998
44.093	28.742	12.038	-4.570	-0.90217
14.385	3.313	-9.887	-25.368	-0.92991
-16.224	-22.764	-32.662	-46.359	-0.91405
-46.462	-49.678	-56.620	-68.209	-0.85035
-75.329	-77.340	-81.933	-91.539	-0.72551
-102.166	-105.327	-108.629	-116.777	-0.52027
-126.649	-133.004	-136.559	-144.047	-0.22164
-148.762	-159.722	-165.344	-173.103	0.16851
-168.759	-184.999	-194.372	-203.313	0.63325
-187.108	-208.607	-222.865	-233.701	1.14515
-204.397	-230.561	-249.990	-263.056	1.67082
-221.221	-251.024	-274.985	-290.093	2.17454
-238.047	-270.192	-297.245	-313.644	2.62279
-255.107	-288.178	-316.369	-332.849	2.99028
-272.335	-304.948	-332.154	-347.280	3.26562
-289.377	-320.293	-344.576	-356.979	3.45360
-305.646	-333.868	-353.752	-362.402	3.57272
-320.420	-345.254	-359.907	-364.282	3.64901
-332.948	-354.041	-363.331	-363.458	3.70869
-342.538	-359.901	-364.335	-360.712	3.77218
-348.642	-362.642	-363.206	-356.641	3.85070
-350.899	-362.211	-360.159	-351.591	3.94564
-349.164	-358.673	-355.313	-345.649	4.04993
-343.512	-352.171	-348.670	-338.676	4.15045
-334.206	-342.877	-340.132	-330.375	4.23078
-321.652	-330.959	-329.526	-320.362	4.27367
-306.335	-316.566	-316.646	-308.244	4.26298
-288.749	-299.832	-301.299	-293.673	4.18523
-269.333	-280.884	-283.355	-276.402	4.03078
-248.429	-259.853	-262.771	-256.311	3.79498
-226.257	-236.881	-239.618	-233.432	3.47889

-202.918	-212.116	-214.076	-207.948	3.08973
-178.419	-185.714	-186.421	-180.183	2.64050
-152.706	-157.827	-157.003	-150.573	2.14871
-125.711	-128.608	-126.208	-119.627	1.63431
-97.393	-98.215	-94.433	-87.870	1.11715
-67.778	-66.825	-62.056	-55.802	0.61438
-36.981	-34.640	-29.419	-23.846	0.13842
-5.223	-1.903	3.185	7.677	-0.30408
27.174	31.102	35.516	38.558	-0.71230

TIME= 3.0000 SEC

INITIAL EFFECTIVE STRESS	NEW PORE PRESSURE
239.3030	0.0000
627.6061	444.3646
925.6061	808.9455
1223.6061	1210.6247
1521.6061	1634.8356
1819.6061	2022.8055
2117.6061	2305.7583
2415.6061	2454.2316
2713.6061	2493.3637
3011.6061	2459.3924